GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1972

1973

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EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

Minister: The Hon. D. G. May, M.L.A.

Under Secretary: G. H. Cooper

Director, Geological Survey: J. H. Lord

By Authority: WILLIAM C. BROWN, Government Printer

1973

16331/4/73

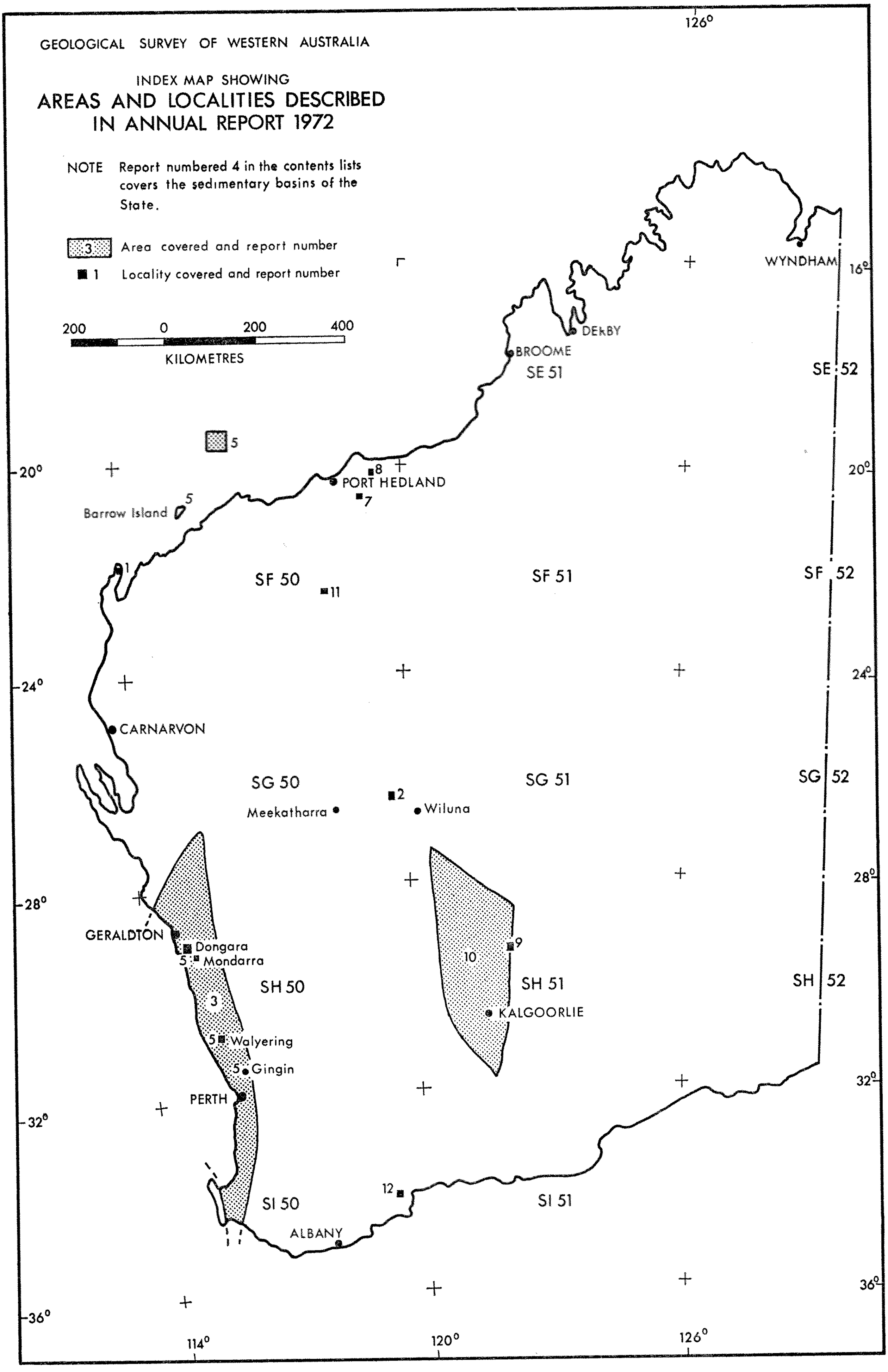

Figure 1. Index map showing areas and localities described in Annual Report for 1972.

DIVISION IV

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Annual Report of the Geological Survey Branch of the Mines Department for the Year 1972

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1972

The Under Secretary for Mines

For the information of the Honourable Minister for Mines, I submit my report on the activities of the Geological Survey of Western Australia during 1972, together with some of the reports on investigations made for departmental purposes.

INTRODUCTION

During 1972 the decline in exploration activity ceased and stability returned to the scene. In fact, by the end of the year there was thought to be an improvement in activity, which will be assisted by a decision to allow Temporary Reserves for all minerals to be taken up again in areas where there is no intense exploration or prospecting activity.

The development of our major deposits of iron, bauxite and nickel are still delayed because of the depressed nature of metal prices and the over-supply position on the world markets. There is a hope that the position may improve during the next year.

Exploration for iron ore was stepped-up with the granting of new Temporary Reserves last May while the feasibility studies of such deposits as McCamey's Monster, Rhodes Ridge and others continued. Goldsworthy Mining Ltd. announced the proving of reserves of 510 million t of ore with a grade of 62.5 per cent Fe and 0.06 per cent phosporus situated in their area C about 300 km south of Port Hedland.

Exploration for bauxite has almost ceased as there are three projects with proven reserves, namely Amax (Mitchell Plateau, North Kimberley), Pacminex (Chittering area north of Perth) and Alwest (northeast of Bunbury) waiting for a recovery in the demand for alumina.

Exploration for nickel continues although plans to open some mines such as Carr Boyd, Spargoville, Widgiemooltha, Redross and Wannaway have been suspended for the present. Exploration has outlined additional reserves on known deposits such as Kambalda with 22,770,000 t containing 3.29 per cent nickel and Agnew 34 million t containing 2.2 per cent nickel. A number of new occurrences have been reported which are still being examined. Two of promise are near Forrestania, 160 km south-southeast of Southern Cross and a low-grade occurrence near Roebourne.

The tempo of oil exploration continued to increase on the northwest shelf with further gas and oil discoveries. The Woodside-Burmah group announced a gas reserve of 566 x 10^9 m^3 while one hole, Eaglehawk No. 1, produced an oil flow of 1,645 barrels per day. West Australian Petroleum Pty. Ltd. made two encouraging intersections near the end of the year in West Tryal Rocks well, where the presence of hydrocarbons was recorded over a total thickness of 46 m and a deep well on Barrow Island encountered high pressure gas at 3,218 m. Both holes are yet to be tested and assessed. The prospects of this area are most encouraging and, although there remains a long and costly period of exploration before the extent of the gas and oil province is finally known, the final outcome will no doubt solve one of the State's major problems, that is the lack of a source of natural fuel and the resultant cheap power for industrial expansion.

There has been a keen interest in the search for uranium, particularly since Western Mining Corporation's find at Yeelirrie (80 km south of Wiluna) claimed to contain 32 million t averaging 0.15 per cent uranium oxide. The uranium occurs as secondary minerals in calcrete and is suitable for open-cut shallow mining. Another reported occurrence is at Mundong Well (290 km northeast of Carnarvon), where uranium mineralization in the form of kasolite occurrs with copper and lead mineralization in a tension vein within a shear zone in a belt of metamorphic rocks which correlate with the Lower Proterozoic Wyloo Group. These two finds have given encouragement for further uranium search on which many companies are now engaged.

Exploration for coal has continued without any noticeable success. The Jurassic deposit of coal at Eneabba has been subjected to feasibility studies and found to be similar in quality to the coal at Collie, suitable for on-site power generation.

In conjunction with the exploration mentioned above the search for other minerals such as copper, lead, zinc, chromium, diamonds, mineral sands, fluorite, barite, kaolin, talc, etc. continues. Considerable interest has been aroused in the potential of lead mineralization in the Devonian limestones of the Kimberley, while several occurrences of fluorite are being examined in detail.

Two lectures followed by field excursions were arranged during the year. The first was centred on Yalgoo covering the Yalgoo and Murgoo 1 : 250,000 sheets. Over 90 persons attended. The second was centred on Ravensthorpe covering the Ravensthorpe and Lake Johnston 1 : 250,000 sheets at which over 110 persons attended. As there is a firm demand for such lectures and excursions, more will be organized during 1973.

STAFF

The staffing situation has been very stable during the year. The only resignation was that of Dr. K. Hooper who decided to return to his University position.

All vacant and new positions have been filled or committed. There are no professional vacancies at present.

It was hoped to arrange a section to deal with environmental geology, however finance was not available for the two positions proposed.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Gibson, A. A., A.W.A.S.M.	Senior Geologist, L3	5/1/72
Wilde, S. A., Ph.D.	Geologist, L1	6/1/72
Cochrane, R. H. A., M.Sc.	Geochemist, L2	12/1/72
Campbell, J. M., B.Sc. (Hons.)	Geologist, L1	1/2/72
Hickman, A. H., Ph.D.	Geologist, L1	20/3/72
Gee, R. D., Ph.D.	Supervising Geologist, L5	8/6/72
Connolly, R. R.	Geologist, L1	22/9/72

Resignations

Hooper, K.	Palaeontologist	1/9/72

Promotions

Cockbain, A. E.	Palaeontologist	23/8/72

CLERICAL AND GENERAL

Butherway, P.	Geophysical Assistant	10/4/72
Branson, G.	Technical Assistant	1/8/72
Boyd, S.	Geological Assistant	23/8/72
McGilligan, M.	Geological Assistant	25/9/72
Veitch, R.	Clerk C–IV	27/11/72

Resignations

Ash, L. A.	Technical Assistant	14/4/72
Bradley, T. R.	Geological Assistant	22/12/72

Transfers In

Nichols, T. J.	Geological Assistant	23/10/72

Transfers Out

O'Rourke, G.	Geological Assistant	4/8/72
Colliss, B.	Geological Assistant	18/10/72
Boyd, S.	Geological Assistant	13/11/72
Abbott, J.	Clerk C–IV	24/11/72

OPERATIONS

HYDROLOGY AND ENGINEERING GEOLOGY DIVISION

E. P. O'Driscoll (Chief Hydrogeologist), T. T. Bestow, R. P. Mather (Supervising Geologists), K. Berliat, A. D. Allen (Senior Geologists), C. C. Sanders, G. W. A. Marcos, J. R. Forth, R. E. J. Leech, W. A. Davidson, A. S. Harley, R. G. Barnes, D. P. Commander, W. P. Balleau, R. I. J. Vogwill, J. Nicholson, and J. M. Campbell.

Hydrogeology

The deep drilling along the Watheroo-Jurien Bay cross section of the Perth Basin was completed and shows that large storages of both domestic and industrial quality water exist in the Mesozoic and Quaternary sediments down to depths of at least 750 m. Drilling on another cross section between Winchester and the coast near Beagle Island has commenced.

Drilling and test pumping of the shallow aquifers of the Perth Basin, north and northwest of Perth, have been carried out by the Metropolitan Water Board and this Department. Areas investigated include Joondalup, Gwelup, Whitfords and Wanneroo. Drilling has commenced in the Lake Thomson area with a view to exploring the potential of shallow aquifers south of the Swan River. A regional assessment of the deeper aquifers of the metropolitan area is continuing.

A study is being made of the effect of drawing pressure water for industrial purposes in the Pinjarra district. It seems likely that at the present rates of use a substantial part of the water is being drawn from storage.

Consultants are continuing their investigation in the East Murchison area for several companies involved in mining feasibility studies. The estimated demand totals 140,000 m^3 per day. The Geological Survey maintains close liaison with these investigations to advise the Government on progress and to further a long term regional water resources appreciation of the State.

Three bores have been drilled on a new major investigation in the Canning Basin east of Port Hedland.

Further deepening of the Cooya Pooya No. 1 borehole to 245 m showed that the groundwater is limited to gravels associated with the Harding River and the weathered section of the Proterozoic volcanics.

At Millstream deepening and test pumping five boreholes to the goethite and Wittenoom Dolomite sections below the calcretes failed to locate the expected larger yields. In the area an investigation was made of a proposal to construct a barrage across the Fortescue River to divert flows onto the calcrete to provide recharge for the Millstream aquifers.

Engineering Geology

With staff at full strength this section has been involved almost entirely with dam site investigations. The following services were provided for the Metropolitan Water Board:

(a) geological advice during dam construction at South Dandalup;

(b) detailed investigations of the Lower Wungong dam site including mapping, seismic traverses, diamond and auger drilling and trenching;

(c) geological mapping for the proposed outlet tunnel from the Canning Dam.

For the Department of Works the following work was done:

(a) a detailed investigation of a proposed dam site at Collie;

(b) a preliminary reconnaissance has been made of five prospective dam sites on the Ashburton River and two on Turee Creek;

(c) the following sites have been studied in the Pilbara:—

  (i) North Pole and Lalla Rookh on the Shaw River—detailed investigation;

  (ii) Kangan Pool on the Sherlock River —mapping and some diamond drilling;

  (iii) Cooya Pooya on the Harding River diamond drilling;

  (iv) Bullinnarwa Pool on the Fortescue River—field mapping commenced.

Advice was given to other Government Departments such as Railways and Main Roads on minor problems.

Near Ravensthorpe a recently discovered lineament in the form of a low scarp was examined. Arcuate in shape, and resembling that formed at Meckering in 1968, the scarp is believed to be of earthquake origin. A trench across the profile showed a development of soil and laterite which suggests the scarp is not of very recent origin.

SEDIMENTARY (OIL) DIVISION

P. E. Playford (Supervising Geologist), R. N. Cope (Production Geologist), G. H. Low (Senior Geologist), J. C. Boegli, R. W. A. Crowe, and W. J. E. van de Graaff.

Petroleum exploration and production data from companies operating in Western Australia were appraised and collated throughout the year. A report was prepared on gas reserves of the North Rankin, Goodwyn, Rankin, Angel, and Scott Reef gas and condensate fields.

Regional mapping of the Phanerozoic rocks around the southern and eastern margins of the Officer Basin was completed. Mapping was carried out on the Neale, Plumridge, Cundeelee, Mingiwal, and Rason 1:250,000 sheets in this area. A drilling programme in the Officer Basin was jointly supervised by the Bureau of Mineral Resources and the Geological Survey to clarify the stratigraphy and hydrogeology.

A regional mapping project was initiated in the northeastern Canning Basin, jointly with the Bureau of Mineral Resources. Mapping of the Phanerozoic of the Billiluna, Lucas, and Stansmore sheets was completed.

Detailed mapping of the Napier Range reef complex was carried out at Windjana Gorge with geologists of the Bureau of Mineral Resources. The joint party also supervised the drilling of a number of shallow stratigraphic holes on the Lennard Shelf.

Geological mapping and test drilling were conducted in the Fitzgerald River area to determine the extent and economic prospects of the Eocene lignite known in the area.

REGIONAL GEOLOGY DIVISION

R. D. Gee (Supervising Geologist), I. R. Williams (Senior Geologist), P. C. Muhling, C. F. Gower, R. Thom, and J. A. Bunting.

The programme of regional mapping of the Precambrian area of the State for publication at a scale of 1:250,000 continued. The progress of mapping is shown in Figure 2.

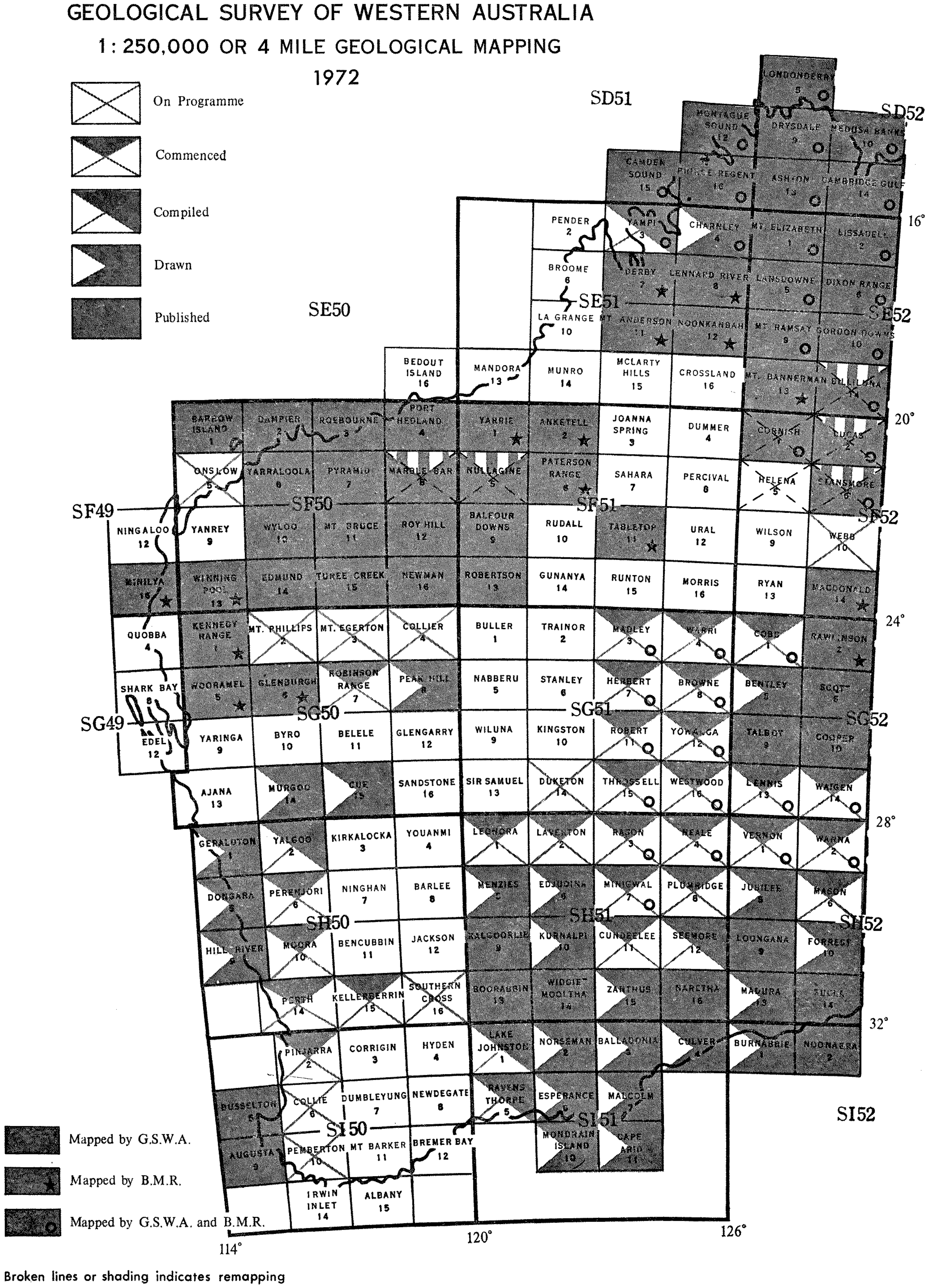

Figure 2. Progress of 1:250,000 or 4-mile geological mapping at end of 1972.

Compilation of the Ravensthorpe, Lake Johnston and Yalgoo sheets was completed. Field mapping of the Leonora, Rason, Neale, Minigwal, Plumridge and Cundeelee sheets was finished. Field work on Laverton sheet was half completed.

Work continued on both the synthesis of the geology of the Eastern Goldfields, and the compilation of the Kalgoorlie and Esperance 1:1,000,000 sheets.

A joint mapping programme with the Bureau of Mineral Resources was carried out resulting in the re-mapping of the Precambrian portion of the Billiluna, Lucas and Stansmore sheets.

Geological excursions on the Yalgoo, Ravensthorpe and Lake Johnston sheets were conducted.

MINERAL RESOURCES DIVISION

J. G. Blockley (Supervising Geologist), J. D. Carter and A. A. Gibson (Senior Geologists), J. L. Baxter, A. H. Hickman, S. L. Lipple and S. A. Wilde.

Compilation of the results of a study of the State's tin deposits continued.

Field and office work were commenced for the compilation of a bulletin on mineral sand deposits, one on vanadium, chromium, tungsten and molybdenum and a revision of the bulletin on the copper deposits of Western Australia.

Tests were carried out on the application of a prototype instrument employing a new geophysical technique for the exploration of mineral deposits; a summary of the results is included in this Report.

Re-mapping of the Marble Bar 1 : 250,000 geological sheet was completed and compilation is in progress.

Mapping of the Precambrian portion of the Perth 1 : 250,000 geological sheet is in progress in conjunction with a study of bauxite occurrences.

Other work included brief inspections of deposits of uranium, diatomite, nickel, barite, marble, fluorite and vermiculite and reports on two road alignments affecting heavy mineral sands and tin deposits.

COMMON SERVICES DIVISION

Petrology—(W. G. Libby, J. D. Lewis, and R. Peers)

The service function of the Petrology section was served by the completion of 62 petrologic reports in 1972. As an aid in the production of significant reports, petrologists continued to visit geological parties in the field and discussions between field staff and petrologists were encouraged. Sixty two petrologic reports were prepared during the year.

As in previous years chemical, mineralogical and X-ray diffraction work by the Government Chemical Laboratories has increased the effectiveness of petrologic reports.

Over 1,680 thin sections and many polished sections were prepared in addition to making sand size analyses and preparing rock samples for chemical and geochronological processing.

A study of the petrology of the sills in the Weeli Wolli Formation is continuing and a project on rodingite in the Laverton and adjacent map sheets has started. The studies of ultramafic lava of the Yundamindra area and alkali syenite of Peak Charles are being completed.

The establishment of a computer-based data storage system has progressed slowly but steadily. Simple input forms now accompany all material submitted for petrologic work and forms for most thin sections described in past petrologic reports have been partly completed, allowing the systematic filing of nearly 3,000 backlogged thin sections.

The need for a quantitative input to the data system has necessitated the development of a standard igneous and metamorphic rock classification for the section. A by-product of this effort hopefully will be clearer communication between petrology and field staff.

The co-operative geochronological programme with the Western Australian Institute of Technology continued through 1972 with the completion of field and laboratory work on several projects in the Gascoyne and Pilbara areas. Liaison and co-operation with the geochronological staff of the Australian National University continued through the year.

Palaeontology—(A. E. Cockbain, J. Backhouse and K. Grey)

During the year 105 file reports were written. As can be seen from the accompanying statistical breakdown of the reports routine palynological work for the Hydrology Division continued to occupy much of the laboratory's time.

Reports written for :	Field of Palaeontology		
	Paly-nology	Micro-palaeontology	Macro-palaeontology
Hydrology and Engineering Geology Division	69	14	1
Sedimentary (Oil) Division	7	3	3
Other	1	2	3
Outside organizations	0	0	0

For most of the year the palynology of samples from the Watheroo Line bores was studied; this work should help considerably in our under standing of the biostratigraphy of the Upper Mesozoic in the Perth Basin. About 9 weeks were spent with a joint G.S.W.A./B.M.R. party in the Canning Basin, collecting Devonian fish from the Gogo Formation and doing well site geology. The study of the Devonian brachiopods collected from the Lennard Shelf area by the Survey over the past few years was continued.

Prior to his departure in August, Dr. Hooper completed a preliminary survey of Cretaceous planktonic foraminifers from the Perth and Carnarvon Basins. Dr. Cockbain was transferred to the Palaeontology Section as officer in charge.

Geophysics—(D. L. Rowston and I. R. Nowak)

Geophysical investigation for the Hydrology and Engineering Division again dominated activites, and as predicted there was a greater demand for seismic refraction work on engineering projects. Surveys were carried out at the South Canning and Lower Wungong dam sites and the Canning Tunnel portals. Additionally, four dam sites at Collie and in the Pilbara were contracted out to geophysical consultants.

Resistivity soundings and seismic refraction techniques were tested at 21 sites in the west Canning Basin to evaluate their application in a regional study of groundwater potential. Whilst the value of the refraction work was clearly demonstrated the significance of the resistivity results is problematical. This investigation will be extended in 1973 and the geophysical interpretation tested by drilling. Velocity inversion problems were encountered in refraction shooting to determine the depth to Archaean basement in another survey in the Port Hedland townsite.

The acquisition of two Gearhart Owen logging units permitted a substantial increase in water bore logging operations. Seventy bores in the Port Hedland region, 21 in the Officer Basin and 60 in the Perth Basin were logged. The number of bores, 151 (43 in 1971), resulted in a total logged length for all runs of 31,600 m compared with 24,000 m in 1971. Depths of the bores ranged between 50 and 760 m.

Laboratory services included 500 conductivity measurements on field water samples, calibration of field salinity bridges and normal maintenance of electronic equipment and instruments.

Geochemistry—(R. H. A. Cochrane)

A programme of reconnaissance scale regional geochemical mapping involving rock and stream sediment sampling was commenced in the Eastern Goldfields. This project was broken into three parts:

(a) a preliminary survey to collect samples regionally throughout the Eastern Goldfields to enable evaluation of the geochemical background. As part of this study samples were collected from most of the areas of known nickel mineralization in the Eastern Goldfields.

(b) this was followed by an orientation stream sediment survey of the Leonora and Laverton 1 : 250,000 sheets to determine the most suitable size fractions for more detailed follow-up work. Early evaluation of these orientation results indicated the suitability of the Leonora sheet for a more detailed survey.

(c) the more detailed survey was commenced in August and the evaluation of the results is continuing.

Technical Information—(J. H. Thom, M. M. Harley, S. J. Commander and S. M. Fawcett)

The library continues to be used extensively by the public. It is estimated that 2,164 such persons availed themselves of the facilities during 1972 and 142 loans were made, while loans to departmental staff amounted to 7,207.

Requisitions raised for photo-copying for the public of out-of-print publications numbered 905. Many requisitions were for several items. Requisitions raised on the Surveys and Mapping Branch for drafting services and photography for the Survey totalled 994.

Twenty-six Records were prepared and issued during the year, while preparation of manuscripts and proof reading of items mentioned in the list of publications below continued. In addition the usual service to public and staff inquiries was given. The development of the Geological Museum continues, and small parties from schools are now being given escorted tours.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

The geological and geophysical projects carried out by the Bureau of Mineral Resources in Western Australia included the following:

(i) Compilation of the 1 : 250,000 geological sheets and bulletins on the Kimberley Division as a joint project with the Survey.

(ii) Completion of the helicopter gravity survey of the State.

(iii) Completion of geological mapping of the Officer Basin as a joint venture with the Survey including seismic surveys and drilling.

(iv) Commencement of geological mapping of the Canning Basin on the Billiluna, Lucas and Stansmore 1 : 250,000 sheets as a joint project with the Survey.

(v) Combined investigation with the Survey of the late Devonian rocks in the Bugle Gap to Oscar Range area including shallow stratigraphic drilling.

(vi) Continuation of the aeromagnetic survey of W.A.

PROGRAMME FOR 1973

HYDROLOGY AND ENGINEERING DIVISION

A. *Hydrology*

1. Continuation of the hydrogeological survey of the Perth Basin including deep drilling.

2. Hydrogeological investigations and/or exploratory drilling for groundwater in the following areas:
   (a) Pilbara-Millstream, Cooya Pooya and Fortescue River
   (b) West Canning Basin
   (c) Murchison and East Murchison—regional assessments
   (d) Town water supplies for the following: Esperance, Cape Le Grand.

3. Hydrogeological investigations for Metropolitan Water Board:
   (a) Regional studies
   (b) Deep drilling at Whitfords, Mirrabooka, Gwelup and Wanneroo
   (c) Shallow drilling at Wanneroo and Lake Thomson.

4. Kimberley Division—hydrogeological assistance to pastoralists as required.

5. Continuation of bore census work in selected areas.

6. Miscellaneous investigations and inspections as requested by Government departments and the public.

B. *Engineering*

1. Pilbara area—further investigations at the following dam sites: North Pole, Kangan Pool, Cooya Pooya, Bullinarwa and probably Gregory Gorge and Munni Creek.

2. Ashburton area: geological mapping of three sites if staff available.

3. Murchison area—field reconnaissance.

4. Darling Range area—continuation of work on South Dandalup, South Canning, Lower Wungong and Collie dam sites—commencement of work on the Harvey River and/or Burekup dam sites.

SEDIMENTARY (OIL) DIVISION

1. Maintain an active interest in the progress and assessment of oil exploration in Western Australia.

2. Evaluate oil and gas discoveries and assess the resources of the State.

3. Continue the sub-surface study of the Perth Basin and the completion of the Bulletin.

4. Continuation of compilation of the mapping of the Officer Basin and begin preparation of the Bulletin.

5. Continue studies of the Devonian of the Canning Basin.

6. Commence surface and sub-surface study of the Carnarvon Basin.

7. Mapping of the Canning Basin in conjunction with the Bureau of Mineral Resources.

REGIONAL GEOLOGY DIVISION

1. Compilation of the Leonora, Rason, Neale, Plumridge, Minigwal, Cundeelee, Marble Bar, Billiluna, Lucas and Stansmore 1 : 250,000 sheets.

2. Continuation of the mapping of the Laverton 1 : 250,000 sheet.

3. Commencement of mapping of the Bangemall Basin on the Mount Egerton, Collier and Mount Phillips 1 : 250,000 sheets.

4. Re-assessment of the regional geology of Eastern Goldfields.

5. Commencement of the mapping of the Precambrian on the Throssell and Duketon 1 : 250,000 sheets.

MINERAL RESOURCES DIVISION

1. Completion of mineral resources bulletins on the tin deposits and mineral sands deposits of Western Australia.

2. Re-map the Nullagine 1:250,000 sheet.

3. Regional mapping of the Darling Range on 1:250,000 scale and study of bauxite occurrences.

4. Assessment of vanadium, chromium, tungsten and molybdenum deposits of Western Australia.

5. Revision of mineral resources bulletin on copper deposits.

6. Miscellaneous mineral investigations as required.

PUBLICATIONS AND RECORDS

Issued during 1972

Annual Report, 1971.

Bulletin 122: The geology of the Western Australian part of the Eucla Basin.

Geological map of Cooper 1:250,000 Sheet (SG/52-10 International Grid) with explanatory notes.

Geological map of Eucla-Noonaera 1:250,000 Sheet (SH/52-14 and SI/52-2 International Grid) with explanatory notes.

Geological map of Medusa Banks 1:250,000 Sheet (SD/52-10 International Grid) with explanatory notes.

Geological map of Montague Sound 1:250,000 Sheet (SD/51-12 International Grid) with explanatory notes.

Geological map of Scott 1:250,000 Sheet (SG/52-6 International Grid) with explanatory notes.

Geological map of Talbot 1:250,000 Sheet (SG/52-9 International Grid) with explanatory notes.

In Press

Bulletin 123: The geology of the Blackstone Region, Western Australia.

Report 2: A reappraisal of the Yule River area: Port Hedland Town water supply, and an appraisal of the effects of long-term pumping in the Lake Allanooka area.

Mineral Resources Bulletin 9: The lead, zinc and silver deposits of Western Australia.

Geological map of Balladonia 1:250,000 Sheet (SI/51-3 International Grid) with explanatory notes.

Geological map of Bentley 1:250,000 Sheet (SG/52-5 International Grid) with explanatory notes.

Geological map of Culver 1:250,000 Sheet (SI/51-4 International Grid) with explanatory notes.

Geological map of Cue 1:250,000 Sheet (SG/50-15 International Grid) with explanatory notes.

Geological map of Esperance-Mondrain Island SI/51-6 and 10 International Grid) with explanatory notes.

Geological map of Forrest 1:250,000 Sheet (SH/52-10 International Grid) with explanatory notes.

Geological map of Geraldton 1:250,000 Sheet (SH/50-1 International Grid) with explanatory notes.

Geological map of Jubilee 1:250,000 Sheet (SH/52-5 International Grid) with explanatory notes.

Geological map of Kurnalpi 1:250,000 Sheet (SH/51-10 International Grid) with explanatory notes.

Geological map of Madura-Burnabbie 1:250,000 Sheet (SH/52-13, SI/52-1 International Grid) with explanatory notes.

Geological map of Menzies 1:250,000 Sheet (SH/51-5 International Grid) with explanatory notes.

Geological map of Norseman 1:250,000 Sheet (SI/51-2 International Grid) with explanatory notes.

Geological map of Peak Hill 1:250,000 Sheet (SG/50-8 International Grid) with explanatory notes.

Geological map of Zanthus 1:250,000 Sheet (SH/51-15 International Grid) with explanatory notes.

In Preparation

Special publication: The geology of Western Australia.

Geological maps 1:250,000 with explanatory notes, the field work having been completed: Billiluna, Browne, Cundeelee, Herbert, Kingston, Lennis, Leonora, Lucas, Madley, Marble Bar, Mason, Minigwal, Neale, Plumridge, Rason, Ravensthorpe, Robert, Seemore, Stanley, Stansmore, Vernon, Waigen, Wanna, Warri, Westwood, Yalgoo, Yowalga.

Records Produced

1972/1 Non-metallic industrial rocks and minerals of W.A., by S. J. Commander and J. L. Baxter.

1972/2 Wells drilled for petroleum exploration in W.A. to the end of 1971, by G. H. Low.

1972/3 Reconnaissance survey of the Pilbara Region, W.A., for limestone, aggregate and clay, by J. L. Baxter.

1972/4 South Canning proposed dam site—report on preliminary geological investigations, by G. Marcos (restricted).

1972/5 Geological inspection of North Pole dam site, Shaw River, by R. P. Mather (restricted).

1972/6 A report on the geology of site E, Collie River storage investigations, by J. Nicholson (restricted).

1972/7 Hydrogeology of the Paroo Calcrete and surrounding areas, Wiluna district, W.A., by C. C. Sanders.

1972/8 Millstream calcrete aquifers, assessment and storage, by J. R. Forth (restricted).

1972/9 Results of investigation into groundwater resources along the lower Gascoyne River for Carnarvon irrigation and town water supplies, by A. D. Allen (restricted).

1972/10 Explanatory notes on the Phanerozoic rocks of the western part of the Collie 1:250,000 Sheet, W.A., by G. H. Low.

1972/11 Agaton project, Perth Basin—geology and groundwater at the Agaton exploratory bore field, by J. R. Passmore and P. Balleau (restricted).

1972/12 Explanatory notes on the Lake Johnston 1:250,000 geological sheet, W.A., by C. F. Gower and J. A. Bunting.

1972/13 Geological reconnaisance of dam sites nos. 2 and 3 on Turee Creek, by R. P. Mather (restricted).

1972/14 North Gnangara sand beds aquifer, by P. Balleau (restricted).

1972/15 Derby town water supply, by R. E. J. Leech (restricted).

1972/16 Exmouth water supply, by J. R. Forth (restricted).

1972/17 Millstream area, proposed artificial recharge, by W. A. Davidson (restricted).

1972/18 Desert farms area, Wiluna—preliminary appraisal of salinity and groundwater movement, by C. C. Sanders (restricted).

1972/19 Explanatory notes on the Phanerozoic rocks of the western part of the Pemberton 1:250,000 geological sheet, W.A., by G. H. Low.

1972/20 Explanatory notes on the Proterozoic and Phanerozoic rocks of the Perenjori 1:250,000 geological sheet, W.A., by G. H. Low.

1972/21 Explanatory notes on the Proterozoic and Phanerozoic rocks of the Moora geological sheet, W.A., by G. H. Low.

1972/22 The natural gas reserves of the Northwest Shelf of W.A. as at 30th September, 1972—an interim report, by R. N. Cope (confidential).

1972/23 Field tests of a prototype 3MHz electromagnetic method in W.A., by N. Watanabe and J. L. Baxter.

1972/24 Geological reconnaissance of dam sites on the Ashburton River, by R. P. Mather (restricted).

1972/25 The geology of the proposed North Pole dam site, Shaw River, by J. Nicholson and J. M. Campbell (restricted).

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J. H. LORD,
Director.

31st January, 1973.

EXMOUTH WATER SUPPLY

by J. R. Forth

ABSTRACT

The Public Works Department have drilled 41 water supply bores in very hard cavernous limestone on the eastern flank of the Cape Range anticline, west of Exmouth Gulf. Above not very permeable Mandu marly limestone, potable water ranging between 500 and 1,500 ppm TDS occurs in the form of a wedge with its upper surface just above sea level, and in contact eastwards with the sea.

The bore field is probably being operated at a safe production rate, and most of the individual bores are being under pumped. However, the recording of pumped salinities will not give sufficient warning if the system is likely to fail, and a set of observation bores to monitor the fresh/saline groundwater interface should be established.

Annual throughflow at the bore field (8,000 m in length) is estimated at 1.35 x 10^6 m^3/year and it is suggested that annual abstraction should not be allowed to exceed 0.81 x 10^6 m^3/year if satisfactory water quality is to be maintained.

The maximum safe pumpage rate for an individual bore depends upon the particular aquifer hydraulic characteristics of each site, and methods are available for this to be approximately calculated for any bore site once a specific capacity test has been done.

Bore spacings are satisfactory in the present bore field, but if the field is extended the bore spacing could probably be reduced to as little as 300 m as long as total pumpage is kept at a safe level.

INTRODUCTION

Exmouth town is 1,200 km north of Perth and is on the eastern side of North West Cape (Fig. 3), a peninsula 21 km from east to west and some 96 km in length. Along its axis a simple anticlinal structure of Tertiary limestones forms Cape Range, bounded on its eastern and western flanks by a flat coastal plain approximately 1.5 km wide.

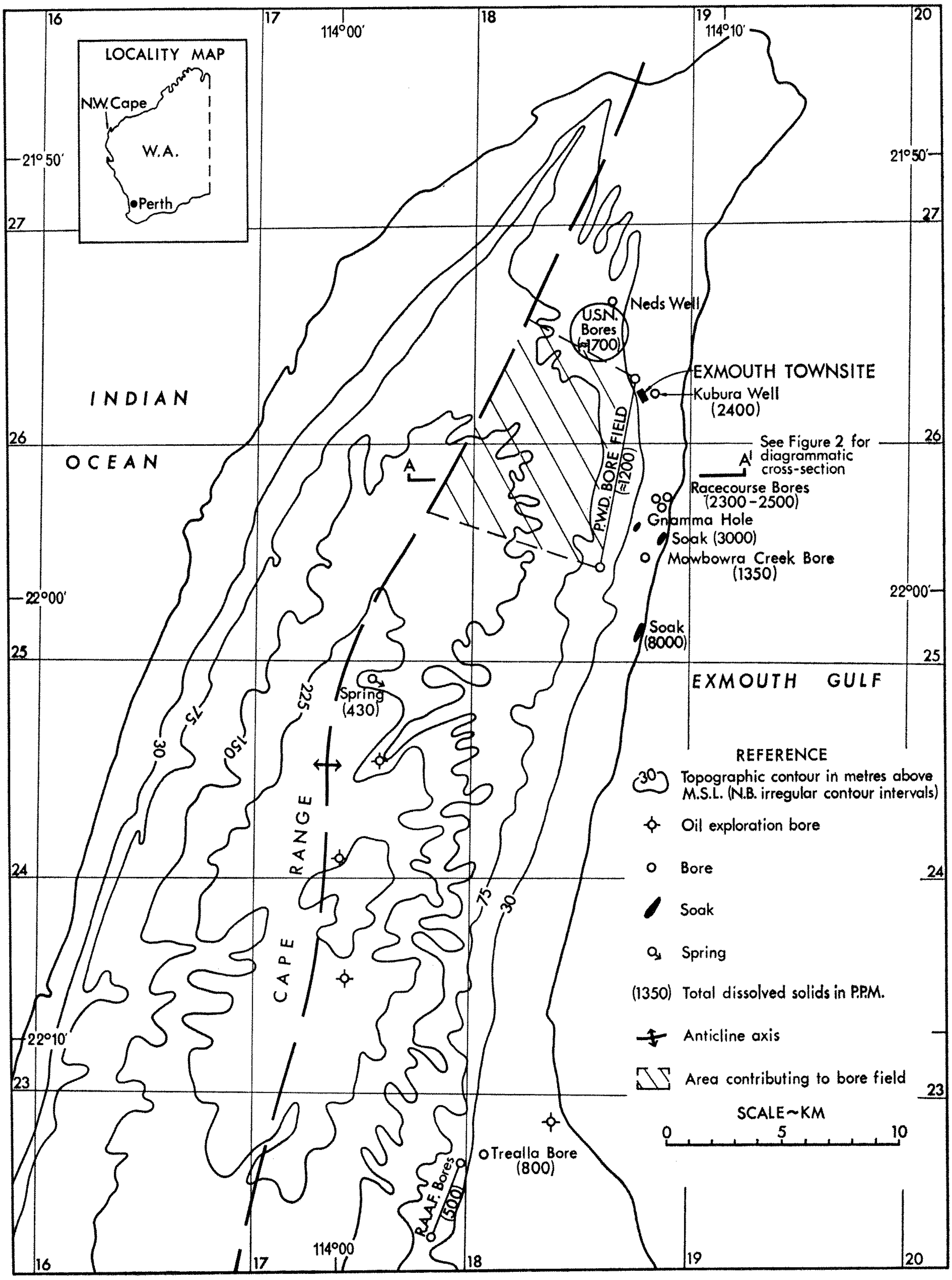

Figure 3. Exmouth water supply location and topographic map.

Maximum elevation is slightly more than 300 m. Stream courses are deeply incised and dendritic in pattern with flat surface divides separating very steep sided canyons.

The present water supply is from bores drilled into cavernous limestone to the west of Exmouth town. Except for one or two bores, water quality has so far been satisfactory, but because some fears have been held for the possible contamination of the supply by saline water from upconing below individual bores, bore salinities and water levels have been monitored.

The only hydraulic information is from specific capacity tests of the production bores.

This report investigates three main problems:

(1) The maximum permissible yield for any individual bore

(2) The maximum total pumpage that can be maintained for the existing bore field

(3) Future data collection to overcome present inadequacies.

Previous work by Sofoulis (1949), Condon and others (1953), O'Driscoll (1963) and Bestow (1966) has been utilized as well as drillers' logs and production records kept by the Public Works Department. These detailed records are described in a fuller report which is not publicly available (Forth, 1972).

GEOLOGY

A general stratigraphic sequence for rocks cropping out in the Cape Range area is as follows:

Age	Formation	Lithology
Recent	Bundera Calcarenite	Clastic limestone
	Mowbowra Conglomerate....	Limestone conglomerate
Pleistocene	Exmouth Sandstone	Calcareous sandstone
	UNCONFORMITY	
?Pliocene	Upper Yardie Group	Calcareous sandstone
Miocene	Lower Yardie Group	Calcareous sandstone
Miocene	Trealla Limestone	Crystalline limestone
	DISCONFORMITY	
Miocene	Tulki Limestone	Crystalline limestone
Miocene	Mandu Calcarenite	Foraminiferal clastic limestone

The well field is on the eastern flank of Cape Range where the Mandu, Tulki and Trealla limestones occur.

The *Mandu Calcarenite* is chalky and friable and over 100 m thick, its upper part only cropping out in very deeply incised canyons. In the lowest exposures it is a fine-grained massive calcarenite and marl, contrasting with its porous chalky nature elsewhere. This variation is of hydrological significance as the marly lower portion could provide a barrier to the downward percolation of rainwater. The only known perennial spring in the Cape Range emerges at the contact between the lower marly rock and the overlying coarse chalky rock.

The *Tulki* and *Trealla Limestones* are very alike, both formations being thick bedded, very hard, crystalline and cavernous. The top of the Tulki Limestone is marked by a band of pisolitic ferruginous limestone.

The Tulki Limestone is 65 m thick at the type section and the Trealla Limestone is 35 m.

Structurally Cape Range is a simple plunging anticline with limestone cropping out above the 30 m topographic contour. Below this level are Pleistocene and Recent sediments. Cavernous flow occurs below the surface and can be seen at the gnamma hole, south of the town, and at Kubura Well. On the plains flanking the anticline, recharge is probably restricted to the drainage lines.

HYDROLOGY

The groundwater is replenished from the annual rainfall (254 mm). Recharge is by direct percolation through the limestone and also by downward soakage through the gravelly stream beds. It appears to ride above the lower marly and impermeable part of the Mandu Calcarenite, a base which has the same anticlinal form as the Cape Range itself. The groundwater is unconfined and has a very flat gradient.

Bore water from the Public Works Department bores typically has a TDS content of 1,000 to 1,200 ppm, with a NaCl content of 700 to 800 ppm and a hardness of around 400 ppm (calculated as $CaCO_3$). The salt content increases towards the sea and is greater at the northern end of the range than at the southern end.

The salinity pattern indicates rainfall recharge and groundwater flow from the range towards the coast. Variation in groundwater salinity is being caused by three independent processes: diffusion or mixing with the seawater; evapotranspiration; and solution.

DIFFUSION

In a cavernous limestone, the seawater/freshwater interface is rarely found as a distinct line of demarcation, as it would be in a uniformly porous and permeable aquifer, but will occur as an irregular zone, broadest near the coastline where the tidal influence is greatest, and narrower and less irregular away from the sea.

The varying bore salinities probably result from irregularities in the zone of diffusion, the groundwater being some 50 m below natural surface at the bore field, so that variations are more unlikely to be due to evapotranspiration. Tidal effects are observable in the bores, so a broad zone of diffusion would be expected, made more complex by the variable hydraulic properties of the cavernous limestone.

The deep saline water can be expected to have a TDS content of 40,000 ppm. Water samples from a spring within Cape Range and from the RAAF bores at Learmonth had TDS contents of about 500 ppm. An infusion of only 2 per cent of the saline water would result in a mixed water salinity of approximately 1,300 ppm which is within the observed TDS variation (600 to 2,300 ppm) at the bore field. Nearer the coast, even higher salinities are likely in pumping bores (Fig. 4).

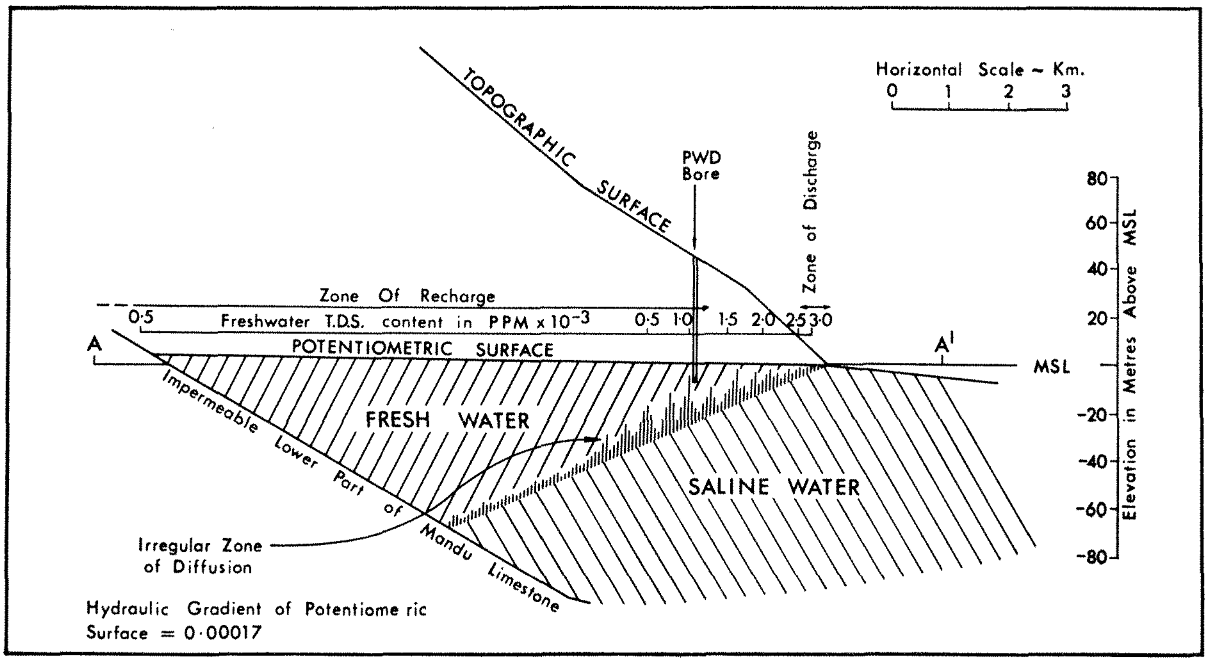

Figure 4. Diagram of freshwater wedge with zone of diffusion and scale of TDS variation from Cape Range to the sea, on section A–A', shown on Figure 3.

EVAPOTRANSPIRATION

Evapotranspiration effects would be restricted to a strip about 500 m wide parallel to the coastline, where salinities of 2,000 to 3,000 ppm have been recorded.

SOLUTION

The groundwater flow is through soluble carbonate rocks, but although the salinity will at first increase towards the discharge zone at the coast, equilibrium will be reached quickly because of the high solubility of these rocks, and there may not be a very noticeable trend of increasing salinity with distance.

Of the three processes discussed, diffusion is the most significant to the P.W.D. bore field and is probably the cause of the variations in salinity in the bores.

AQUIFER RECHARGE

Recharge to the area contributing to the P.W.D. bore field has been estimated by two methods, neither being very reliable because of data inadequacy, but yielding comparable results. Applying Darcy's Law to the data available gives the annual increment from rainfall as 25 mm/year, or 9.8 per cent of the annual rainfall. Assuming a sodium chloride content of 25 ppm for rainfall, the annual recharge comes to 9.8 per cent of the rainfall, the two figures being in remarkably close agreement. This implies that annual recharge can reasonably be accepted as being slightly less than 10 per cent.

BORE FIELD DESIGN AND OPERATION

The safe permanent operation of the bore field depends on three things: the maximum permissible pumpage for any individual bore must not be exceeded or upconing of the underlying saline water will result; pumping from one bore must not cause interference and undue draw down at neighbouring bores; the total output from the whole scheme must not exceed some yet to be determined "safe yield," which must be less than total annual throughflow.

Using formulae given by Bennett and others (1968), calculations suggest that the present rates of pumping from Bores 7, 20, L and R are probably marginal, but all other bores would be classified as quite safe and are being operated below their maximum permissible pumpages. Bennett and others (1968) derived their equations for alluvial sediments and not for cavernous limestone, which casts some doubt on the validity of using the equations, but the most important factor used is the density difference between the pumped water and the underlying saline water, and this is not a property of the aquifer material.

Results obtained by using the Theis (1935) equation to calculate interference drawdowns were also satisfactory, indicating that interference between neighbouring bores will be negligible.

Total pumpage from the bore field must be maintained at some level less than annual throughflow, otherwise the seaward flow will be so reduced that the thickness of the freshwater wedge down-gradient from the bore field will steadily decline. If this decline were allowed to proceed too far, salt water upconing would eventually occur.

From the available data the upward limit to the amount of throughflow that can be pumped cannot be calculated with any accuracy. With better aquifer hydraulic data and a good potentiometric map it would be possible, by flow net analysis, to establish the safe upward limit to total pumpage. As this cannot be done an estimate only can be made, and this is put in the range of 60 to 70 per cent of annual throughflow.

Annual throughflow has been calculated at 1.35×10^6 m^3/year, and "safe yield" is tentatively put at $0.6 \times 1.35 \times 10^6 = 0.81 \times 10^6$ m^3/year.

From the data available, the present rate of abstraction (approximately 0.7×10^6 m^3/year) is judged to be safe, and could be slightly increased.

From specific capacity tests a mean value of 170 m/d has been calculated for the lateral hydraulic conductivity (Table 1), which is feasible for cavernous limestone. Any errors in its estimation will directly affect estimates of recharge, "safe yield" and maximum permissible pumpage. The very wide variation in the tested values (10 to 1,000 m/d) indicate that further pump testing for other than specific capacity information will not be worthwhile because of this wide variation.

TABLE 1. CALCULATION OF HYDRAULIC CONDUCTIVITY

(See Walton, 1962, Figs. 2 to 8)

Bore	Pump Rate m^3/d	Draw-down m	Screen Length m	T m^3/d/m	K_1 m/d
1	125·5	0·126	2·7	900	330
3	125·5	0·254	2·7	405	150
4	125·5	0·051	2·4	2450	1000
5	125·5	0·051	2·7	2450	910
6	125·5	0·051	2·7	2450	910
7	130·9	1·36	1·7	65	24
8	130·9	0·91	2·7	106	39
9	130·9	0·61	2·7	156	58
11	130·9	0·91	3·4	106	31
13	130·9	0·76	2·7	130	48
14	130·9	0·305	6·1	350	57
15	130·9	0·71	6·1	140	23
16	130·9	0·15	4·6	780	170
17	130·9	0·76	6·1	130	21
20	130·9	1·22	6·1	75	12
21	130·9	0·455	6·1	230	38
23	130·9	0·61	5·5	160	29
J	130·9	0·305	6·1	350	57
K	130·9	0·06	6·1	2150	350
L	130·9	1·52	6·1	59	10
M	130·9	1·22	6·1	75	12
N	130·9	0·61	6·9	156	23
O	130·9	0·152	6·1	770	130
P	130·9	0·253	6·1	430	70
Q	130·9	0·28	6·1	390	64
R	130·9	1·52	6·1	59	10
T	130·9	0·38	6·1	280	46

rw = 0·076 m t = 0·33 days T = 585 K = 171
$\bar{K}$ = 170

NOTE : K_1 = lateral hydraulic conductivity.
m^3/d = cubic metre per day.
T = time.
rw = bore radius.

Absolute values of vertical hydraulic conductivity are not required for the estimation of maximum permissible yield. Vertical hydraulic conductivity is certain to vary widely as does the lateral component. A conservative ratio of 10 for lateral to vertical hydraulic conductivity can be used when calculating maximum permissible pumpage for any bore.

FUTURE INVESTIGATIONS

Bores will vary so widely in their individual behaviour that it will not be worthwhile to investigate problems associated with individual bores. The hydraulic properties of the karstic aquifer will similarly vary and it is not recommended that investigations be made to collect hydraulic data for a theoretical solution to management problems.

Instead, future work should be directed solely towards obtaining suitable data to enable the bore field to be adequately monitored and managed, the critical parameters being the position of the interface, and the groundwater levels.

POSITION OF INTERFACE

Monitoring of the position of the interface in observation bores is the most important mangement tool. Interface movement (as distinct from upconing below an individual bore) will be slow, and if the field is overpumped sufficient warning can be expected to allow the scheme to be expanded. The observation bores should be drilled in lines of three or four at right angles to the coast line, with each bore being drilled to approximately 30 m below sea level, capped, and with a concrete collar to exclude surface runoff.

Two lines of bores are recommended for monitoring the existing bore field, and a third to monitor the interface position where it is undisturbed by pumping.

The same bores could be used for measuring groundwater levels, to establish hydraulic gradients, and for correlation with interface movement. Because hydraulic gradients and changes in water levels are small accuracy of not more than $\pm$ 5 mm is needed.

The effects of changes in water level will not be obvious. Using present data it has been calculated that a change in water level of 75 mm (which could not be determined with the present instrumentation) would result in a reduction in freshwater storage of almost 20 per cent.

ADDITIONAL SUPPLIES

Production from the present bore field can be slightly increased, but if future monitoring indicates overpumping, the present line of bores should be extended farther south with a bore spacing of no less than 300 m. When the seawater-freshwater interface position is better known screen designs could be improved to allow higher safe pumping rates.

At present some bores are not used because of high salinity. This is thought to have resulted from localized upward diffusion of more saline water and redrilling about 100 m away might be worthwhile.

RECOMMENDATIONS AND CONCLUSIONS

1. Present total pumpage apparently is at a safe level.

2. Most individual bores are probably being underpumped.

3. Insufficient data are available to be positive about conclusions 1 and 2.

4. Monitoring of the scheme should be improved, both as regards water levels and salinities. Salinity monitoring will only reveal when the system has failed and not give sufficient warning before failure. Bores should be installed to measure changes in the interface position, and in water levels. A salinity logger would be useful for this work.

5. No investigations to collect further hydraulic data seem worthwhile, because of the obvious wide variation in aquifier properties.

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HYDROGEOLOGY OF A CALCRETE DEPOSIT ON PAROO STATION, WILUNA, AND SURROUNDING AREAS

by C. C. Sanders

ABSTRACT

Calcrete is a valley-fill limestone deposit occurring in the arid interior of Western Australia. In places it forms excellent aquifers. One such aquifer on Paroo Station, has been explored by drilling and pump testing, which has indicated that up to 3.62 x 10^6 m^3/year of potable water may be pumped from the area without reducing the volume of water in storage, provided that normal recharge takes place. This annual value is the rate of downstream groundwater discharge, but natural losses by evapotranspiration and lateral underflow into the confining rocks at the margins of the calcrete constitute an additional discharge estimated to be 0.87 x 10^6 m^3/year. These losses would be reduced, if not eliminated, if a total of 4.49 x 10^6 m^3/year of

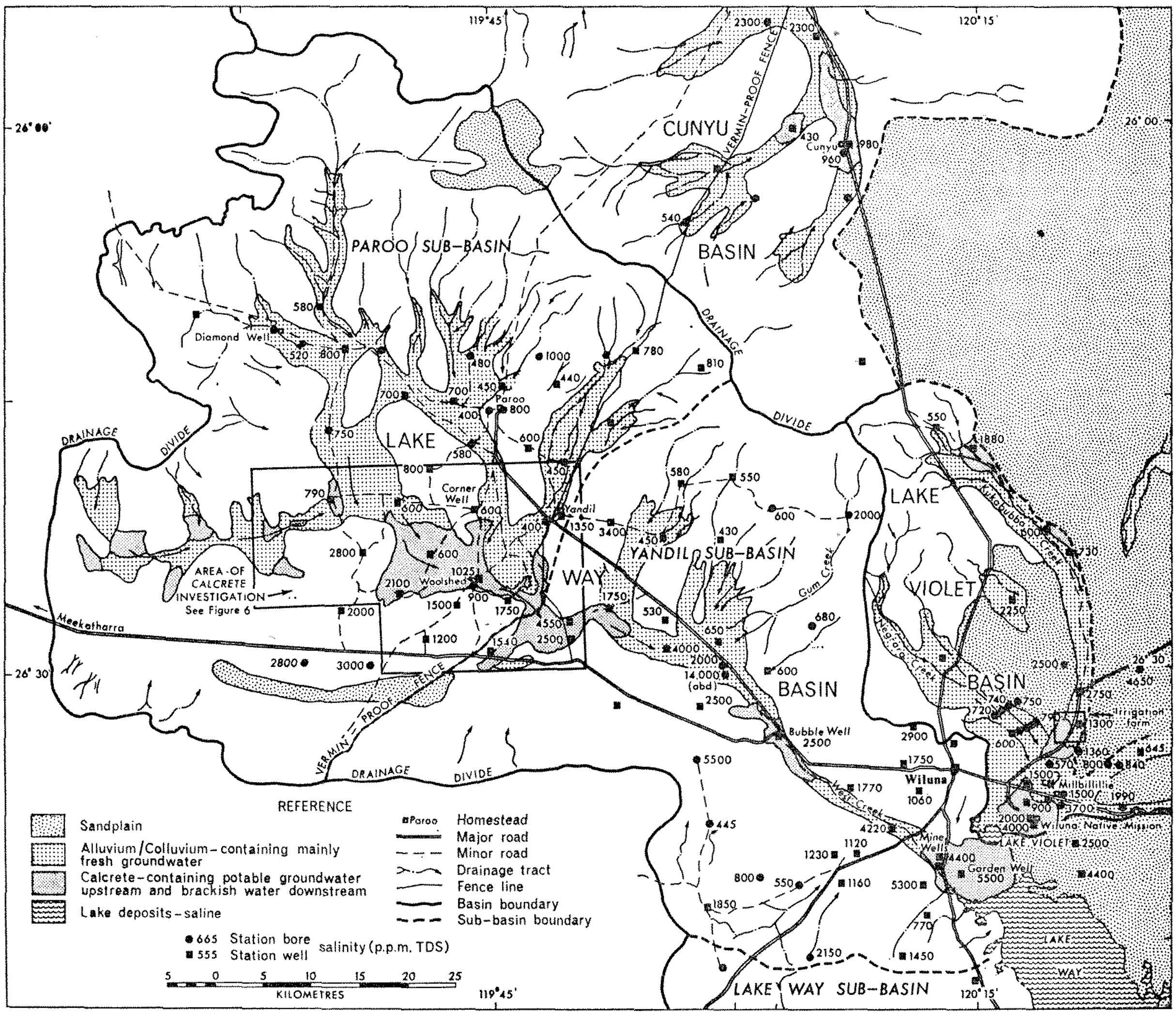

Figure 5. Paroo Station project, Wiluna. Paroo and Yandil catchment areas.

water were to be abstracted. Groundwater in storage in the aquifer has been estimated to be 104.4 x 10^6 m^3. Recharge occurs directly by the infiltration of rainfall on to the calcrete and indirectly from runoff on to the aquifer from the surrounding basement rock and alluvial catchment area of 2,300 km^2. Other calcretes in the Wiluna district, although not tested, may be exploited for brackish industrial quality groundwater, the reserves of which could be substantial. Uranium and thorium enrichment in the calcrete is noted.

INTRODUCTION

A calcrete on Paroo Station, 56 km west of Wiluna, occupies part of a 2,300 km^2 catchment area, the Paroo Sub-basin of the vast Lake Way Basin that is drained internally into saline Lake Way, south of Wiluna (Fig. 5). The full Lake Way catchment area is 5,000 km^2. Its drainage valley is some 100 km in length and from 1 to 10 km in width, being broadest on Paroo Station, where the calcrete fill is best developed and the contained groundwater less saline than elsewhere. The terminal salt lake is at an inland base level of 490 m above mean sea level, and acts as an evaporative basin. The drainage divides for the system are in Proterozoic rocks at an average height of 580 m above mean sea level.

Paroo Station straddles the Meekatharra-Wiluna Road immediately west of the No. 1 Vermin Proof Fence, on the Glengarry 1:250,000 International Grid Sheet.

The investigation of the calcrete was undertaken as part of a broad programme to delineate areas of usable groundwater in the Wiluna district. It was already known (Ellis, 1953; Chapman, 1962) that large supplies of potable or near-potable water could be extracted from calcrete, and since the rapid expansion of mining activities in the region between Kalgoorlie and Wiluna had caused an increased draw on the established Goldfields Water Supply Scheme, an alternative scheme was warranted. At Wiluna, records show that for a 13-year period of peak gold mining operations, about 4.5 x 10^3 m^3 of potable water were pumped daily from wells in calcrete, without any apparent serious aquifer depletion.

Following a hydrogeological reconnaissance of calcrete in the East Murchison Goldfield District in 1968 (Sanders, 1969), the Geological Survey undertook the drilling and testing of the calcrete on Paroo Station, which is the largest feature of its kind in the district. For the investigation, 16 bores were drilled, some with associated observation wells, in and about the calcrete (Fig. 6). Ten of the bores were pump-tested at yields of up to 1.3 x 10^3 m^3/d, for 8 hours duration. This work has been previously reported (Sanders, 1971).

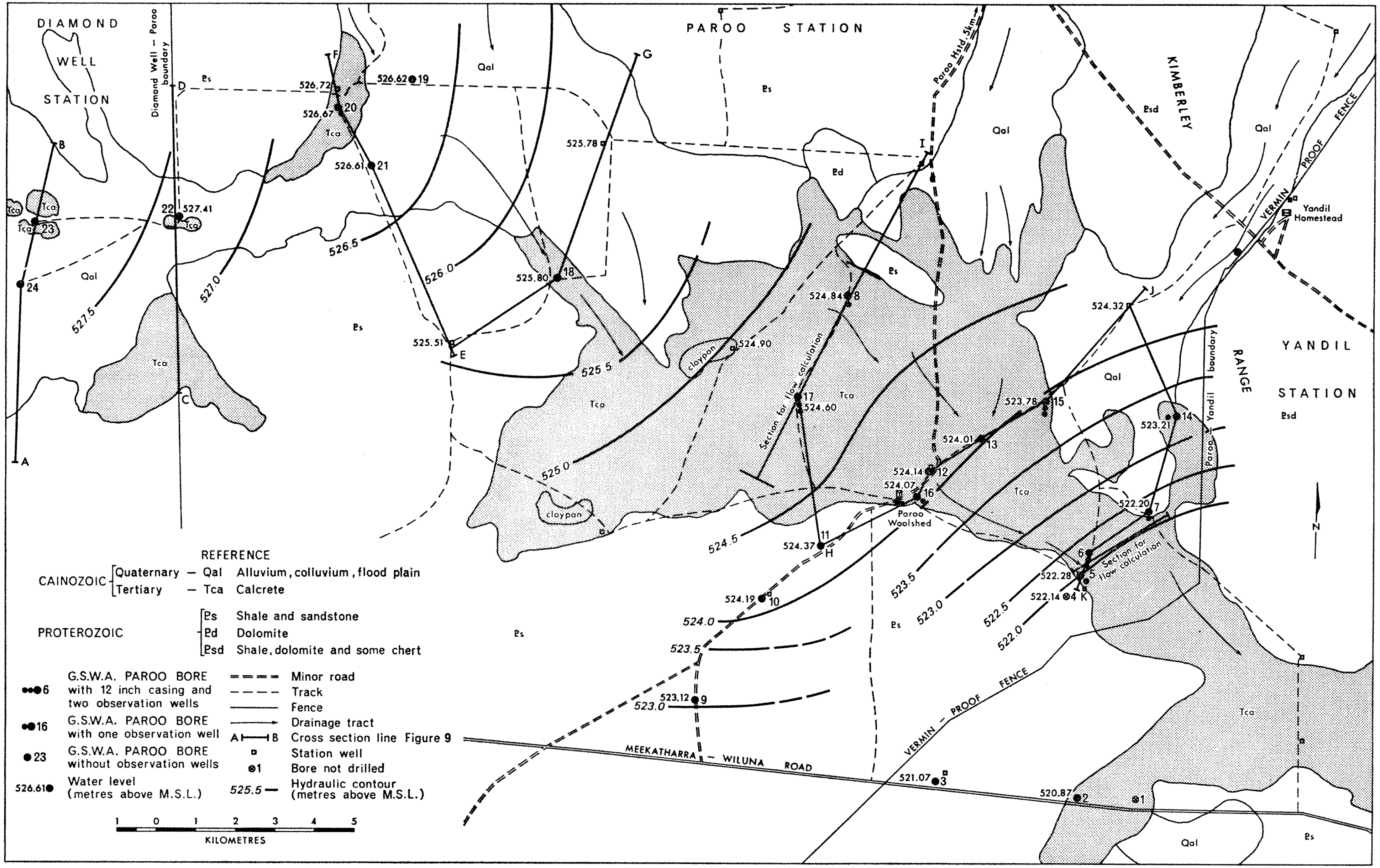

Figure 6. Paroo Station project, Wiluna. G.S.W.A. exploration water bores, position and geological map.

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Analysis of the pumping test data indicated that a precise evaluation of the calcrete aquifer parameters could not be made without further testing of some of the bores at higher pump yields of up to 3.3 x 10^3 m^3/d, and for durations up to 16 days. This work was undertaken in 1971 after three bores (6, 15 and 17) had been reamed out to take 12-inch standard casing, which was slotted from the standing water level to the base of the aquifer. Two fully penetrating observation wells were also constructed at each test site. Some additional drilling was also done in the northwestern part of the valley (bores 19 to 24), in an area only partly calcreted, and not previously explored.

CLIMATE AND GEOMORPHOLOGY

The climate of the Wiluna District is arid, with a mean annual rainfall at Yandil Station of 211 mm (over a 24-year period). This falls mainly between January and June (Chapman, 1962). Unreliable rainfall measurements have been made at Paroo homestead since 1966.

Evaporation rates from free water surfaces in the district are extremely high. Annual values for the East Murchison Goldfield from a British Standard 3-foot-diameter evaporimeter are between 2,286 and 2,794 mm per year.

The area lies within the Salinaland Physiographic Division of Jutson (1950), characterized by internal drainages terminating in salt lakes. The division has a general elevation of between 490 and 610 m above sea level, and forms part of the Great Plateau of Western Australia, which is developed mainly over the Archaean Yilgarn Block south of Wiluna. The plateau has a subdued relief with greatest surface expression in the Proterozoic province just north of Wiluna.

The plateau has two physiographic elements: a higher Old Plateau and a lower New Plateau (Jutson, 1950).

The Old Plateau is considered to be a pre-Eocene peneplain, which has undergone rejuvenation since the late Tertiary as a result of southeastward tilting of the Westralian Shield. The renewed erosion degraded the existing valleys and sheet-stripped the deep soils, eventually re-exposing the Archaean rocks and forming the New Plateau at a lower level.

The youthful erosion was soon checked by the onset of an increasingly arid climate, which caused the alluviation of trunk valleys as the stream flow fell. Extensive colluvial and alluvial sheets and fans were deposited over the New Plateau surface by the smaller streams.

The Old Plateau is now represented by high-level sandplain and extensive lateritized surfaces eroded in places into undulating hills, and usually ending in south-facing breakaways. The plateau stands between 9 and 30 m above the younger plains, but in areas of Proterozoic sandstone, the most resistant rock to erosional lowering, residual hills stand up to 60 m above the New Plateau.

The drainage pattern of the Old Plateau has two components, both being geologically controlled (Fig. 5). A minor north-south component follows the structural trend of the Proterozoic sediments and results in a dendritic pattern. The major drainage component is southeastward along the regional grain of the Archaean rocks which crop out south and east of Wiluna, and is a trend imposed on the overlying Proterozoic rocks.

GEOLOGY.

The area of investigation is on the Glengarry 1:250,000 geological sheet, which has not yet been entirely mapped. Sofoulis and Mabbutt *in* Mabbutt and others (1963) have outlined the geology from a reconnaissance survey done in 1958. The rock sequence consists of slightly deformed Proterozoic sediments, Tertiary laterite and duricrust, calcrete valley fills, and Quaternary alluvial/colluvial deposits (Fig. 6).

PROTEROZOIC SUCCESSION

The Proterozoic succession consists of gently folded dolomite, shale, silstone, sandstone and chert, with some intrusive volcanics, which unconformably overlie Archaean basement rocks. The sediments are correlated by Sofoulis and Mabbutt with part of the Upper Proterozoic Nullagine "system", which was first recognized as a large sedimentary province by Talbot (1926). However recent work by MacLeod (1969) on the Peak Hill 1:250,000 geological sheet, directly to the north of Glengarry, suggests that these rocks probably belong to the Middle Proterozoic Bangemall Group (Daniels, 1966), which occurs extensively in the Pilbara Region to the north.

Near Paroo homestead the Proterozoic sequence is represented by shale, siltstone, dolomite and standstone, which crop out as hills. These are dissected along north-south-trending fractures and joints into undulating surfaces with south-facing breakaways up to 15 m high. Drainage is southward into the central calcrete. South of the calcreted area, erosional lowering has removed much of the Proterozoic rocks leaving few low, residual hills, and large areas of gibber plain floored with angular chert and shale fragments. Here drainage is poorly defined.

CAINOZOIC SUCCESSION

These rocks are thin deposits resulting from the protracted degradation of the Proterozoic sequence.

Tertiary ferruginous laterite and siliceous duricrust cap most of the older surface remnants and form extensive breakaways at the headwaters of tributaries of the trunk drainage system. Sandplain, lake deposits, and red silty sands cemented into a siliceous hardpan, make up more than 50 per cent of the land surface, with alluvial-colluvial and calcrete valley-fill deposits occupying about another 5 per cent. The inter-relationship of these units is illustrated in Figure 7. The hardpan areas and the northern tributary valleys of the Paroo depression often form extensive flood plains during rare periods of high rainfall.

The calcrete occurs as a widespread cover over the floor of the main drainage depression, and is a limestone and opaline silica deposit generally associated with fluviatile sediments.

Calcrete

The term calcrete was first suggested in the literature by Lamplugh (1902) to describe some lime-cemented beach detritus occurring in Ireland, but was later used (Lamplugh, 1907, p. 198) to denote some South African superficial, indurated calcium carbonate deposits formed under arid conditions.

The Geological Survey of W. A. uses calcrete to define those "limestone deposits associated with fluviatile valley-fill sediments that occur in both broad fossil valleys and in existing trunk drainage systems of the arid interior of the state" (Sofoulis, 1963; Sanders, 1969). The limestones occur mainly at valley floor level characterized by an indurated nodular surface, that may show karstic features such as sink holes, solution pipes, mounds and cavities. Below ground level the deposit may be powdery, granular or massive, and contain unconsolidated detrital bands and cellular opaline silica layers. The sequences in places attain thicknesses up to 30 m but are usually of the order of 5 to 10 m thick. They are partly saturated with groundwater, the water table usually lying at a shallow depth.

Other organisations and investigators (e.g. Sanders, J., and Friedman *in* Chilingar, Bissell and Fairbridge, 1967, p. 175), usually group calcrete with caliche and kankar (kunkur, kunkar). Goudie

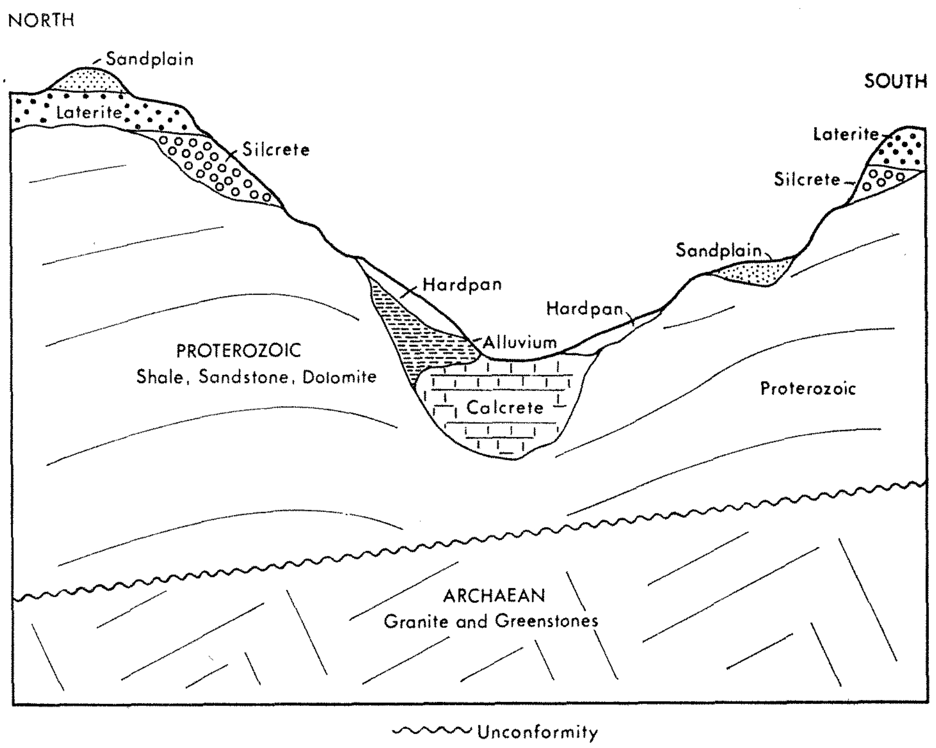


Figure 7. Relationship of rock units north-south through Paroo Sub-basin. Vertical scale greatly exaggerated.

(1972) defines calcretes as "terrestrial materials composed dominantly but not exclusively of calcium carbonate, and involving the cementation of, accumulation in and/or replacement of greater or lesser quantities of soil, rock or weathered material primarily within the vadose zone . . . ". This definition fits the rock type recognized by the Geological Survey as kankar. These are superficial, indurated, nodular or sheet calcium carbonate deposits a metre or so thick, developed within the weathered soil profile, commonly over basic rocks, and found throughout the arid interior of Western Australia.

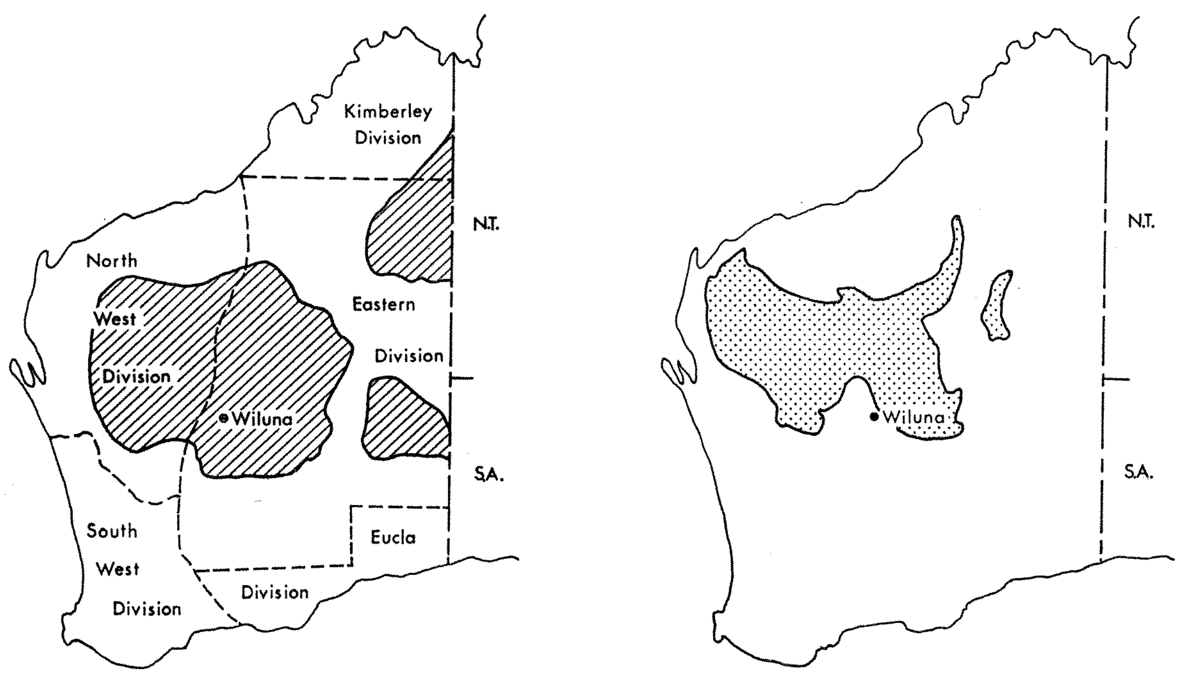
Most valley calcretes above the water table have a kankar-like surface, but their thickness and confinement to drainage lines indicate a genetic and depositional control, at least below the water table, different from that of kankar.

Sofoulis (1963) suggested that calcretes were probably formed as primary chemical precipitates from solution in ground and surface waters, especially in "ponded" sections of the drainage after cessation of a past period of humid climate. Sanders and Harley (1971) consider that carbonate precipitation in blocked sections of drainage lines under arid conditions can explain some small areas of calcrete, but that slow replacement of fluviatile silt, sand and gravel by calcium carbonate precipitated from percolating carbonate-saturated ground and soil water is the main mechanism in calcrete formation. Silica taken into solution is often reconstituted into chert (opaline silica) at about the water table. Evidence for the replacement origin is provided by the common occurrence of localized patchy calcrete within extensive fluviatile sediments; also, in laboratory examination of bore cuttings, calcite is seen to interfinger and penetrate relict alluvial grains including quartz. Moreover the groundwater in situ pH is high, commonly between 8.0 and 9.5, a condition reported by a number of authors (e.g. Walker, 1962) as being favourable for silica-carbonate inter-reaction.

Recent work on the occurrence of Western Australian calcretes, by Lowry (1971) and Sanders and Harley (1971), indicates that their areal distribution generally follows the line of outcrop of the Bangemall Group sediments (Fig. 8). The source of lime for the calcretes is thought to come from dolomites of this province; there is evidence for this from the trend of the drainages, and from chemical analyses of both calcrete and its contained groundwater. Generally there is a lack of major calcrete deposits in areas away from the Bangemall Group. Some calcretes do occur in the Archaean province south of Wiluna and in the Officer Basin east of Wiluna, but they are mainly located in ancient drainage valleys demonstrably issuing from the Proterozoic Province (Sanders, 1969; Sanders and Harley, 1971). The Bangemall sediments probably existed at least as far as 180 km south of Wiluna, but have been eroded back to the position they now occupy. Evidence for the southward extent of the Proterozoic rocks is suggested by remnant hills such as Gabanintha, 40 km southeast of Meekatharra, and outliers occurring 60 km south of Lake Carnegie, east of Wiluna. Also, near Ockerburry Hill, 180 km south of Wiluna, buff coloured silstones, known popularly as "Weebo stone" are regarded as Proterozoic.

Calcium carbonate leached from the Archaean ultrabasic rocks has probably helped in the formation of some calcretes, especially where drainage from the Proterozoic sediments does not occur. Such calcretes are usually thin and rarely exceed 10 m in thickness. One important valley-fill calcrete, apparently unrelated to drainage from the Proterozoic succession, occurs near Cue, 260 km southwest of Wiluna. The lime source for this deposit is thought to come from calcium-rich ultrabasic and mafic rocks which surround the calcrete depression.

Chemical analyses of calcretes from Paroo, Wiluna and Cue show them to be high magnesium limestones, averaging nearly 4 per cent magnesium. The Paroo groundwater has a Mg/Ca ratio in excess of 1, when in most groundwaters the ratio is usually about 0.2. The nearest known source of magnesium to the calcrete of Paroo is the Bangemall dolomite. However, groundwaters in calcrete in the Archaean area to the south, for example at Cue, also have Mg/Ca ratios in excess of unity. This magnesium must come from leaching of ultrabasic rocks.



Distribution of calcreted drainage deposits (shaded) after Sofoulis, 1963, Sanders, 1969, Sanders and Harley, 1971.

Distribution of Middle Proterozoic Bangemall Group Rocks (shaded) partly after Daniels, (1966.)

Figure 8. Sketch maps of W.A. showing areal distribution of calcrete and Middle Proterozoic sediments.

Radioactivity in Calcretes

At present calcrete is beginning to assume economic importance as well as being of hydrological significance. The rock appears to absorb and concentrate uranium and thorium, from solution in the percolating groundwater. This was first noticed at Paroo in 1969 after borehole logging with a gamma-ray scintillometer probe. Limestones normally exhibit little gamma-ray activity, but it was noticed that some borehole graphs showed strong anomalous gamma-ray peaks, mainly at about the level of the water table. To test whether traces of radioactive materials were causing the peaks a sample of kankarized surface calcrete and some cuttings of opaline silica from the water table were analyzed for uranium and thorium. A sample of nearby dolomite and some calcrete at Wiluna were analyzed at the same time (Table 2) as a check on the distribution of any radioactivity.

TABLE 2. THORIUM AND URANIUM CONTENT OF SOME CALCRETE AND DOLOMITE SAMPLES

Sample Description	GSWA No.	Parts per million	
		Thorium	Uranium
Calcrete (opaline silica) from Paroo 6, 6 m depth	10897	130	10
Calcrete at surface Paroo 11	10894	70	5
Dolomite at surface 1 km west of Corner Well	10891	60	less than 5
Calcrete from Negrara Creek, Wiluna 1:250,000 Grid ref. 325 702	10896	75	5

Analysis by Government Chemical Laboratories

These analyses indicate greater enrichment of radioactive materials within the calcrete than would normally be expected, particularly the thorium value. It is assumed that radioactive particles are transported from their provenance by groundwater and where the chemical environment is favourable they are precipitated as complex minerals. Some bore water samples have been submitted to the State X-ray Laboratories for radiometric analysis. Radioactivity within the groundwater was shown to be as much as 70 times greater than the normal background activity of between 10^{-4} and 10^{-3} ppm (Hem, 1970, p. 212). However, the actual elements causing the activity in solution could not be definitely identified.

In 1971 and again in 1972, uranium finds by mining exploration companies were made in calcreted or partly calcreted terrain. These discoveries are in the Archaean province south of Wiluna, and it is suggested that here the uranium was probably leached from granitic rocks of the area and absorbed and enriched within the calcrete. Some radioactive materials obviously occur within the Bangemall sediments as indicated in Table 2, and calcretes nearer these rocks may require closer examination.

Age of Calcrete

The age of most calcretes is not firmly established, although recent mapping and drilling in the East Murchison Goldfields District indicates that calcretization is occurring at present. For example some calcretes within extensive fluviatile sediments east of Wiluna (Fig. 5), are patchy both laterally and vertically, and examination of drill cuttings suggests that carbonate replacement is proceeding. However, Mabbutt and others (1963) regard the Wiluna calcretes as being Tertiary and having a possible correlation with the Oakover Formation of the Pilbara Region. On the other hand, MacLeod (1969) assigned an undetermined Quaternary age to calcrete mapped on the Peak Hill Sheet. At Paroo the calcrete development is thick and broad, and is often overlain by alluvial wash and colluvial detritus. The volume of calcrete at Paroo, estimated from mapping and drilling data is 1.0 x 10^9 m^3, which is of sufficient bulk to postulate a long period of development. The calcretization process probably immediately followed alluviation of the Lake Way trunk drainage system. For this reason the Paroo Calcrete is mapped as Tertiary in this report, although it is realized that calcrete development has probably continued to the present.

CATCHMENT AREAS

The calcrete at Paroo forms part of the Lake Way drainage basin, which is divisible into three large sub-basins: Paroo Sub-basin, Yandil Sub-basin and Lake Way Sub-basin (Fig. 5).

PAROO SUB-BASIN

The central calcrete depression between bore 18, and the Vermin Proof Fence, has an areal extent of at least 90 km^2. The sub-basin divide is essentially at right angles (northeast-southwest) to the southeast drainage trend, and is more or less followed by the line of the No. 1 Vermin Proof Fence.

West and north of the main calcrete and tributary to it, are 80 km^2 of strongly cemented alluvium, some minor calcrete and 155 km^2 of interconnected alluvial/colluvial flood plain, respectively. Gradients are low, averaging 0.28 x 10^{-3} for the calcrete, and 2.0 x 10^{-3} for the alluvial/colluvial areas. Creek channels are poorly developed and scoured water courses occur mainly in the northern part of the catchment where erosion of the Proterozoic hills is most active.

The calcrete surface has been eroded in places to a metre or so below the surrounding ground level by irregular flood channels floored by calcrete rubble and fine alluvial debris. The channels are often fringed with river gum trees (*Eucalyptus camaldulensis*). The largest of these erosional features is along the northern boundary of the calcrete between bores 6 and 7 (Fig. 6).

Groundwater occurs nearly everywhere in the sub-basin, provided that a bore is drilled deep enough. At its shallowest it is about 4.3 m below ground level in the calcrete. Water quality is best in the alluvial areas where the total dissolved solids range from 450 to 710 parts per million. The groundwater is deepest, 38 m below ground level, in bores constructed south of the Meekatharra-Wiluna Road, and also quality is poor (Fig. 5).

At present groundwater is used for stock and for very limited domestic consumption and irrigation.

YANDIL SUB-BASIN

The Yandil Sub-basin comprises a catchment area of 2,700 km^2 of which 80 km^2 is calcrete occupying parts of the central drainage tract. Alluvial and colluvial deposits make up another 100 km^2 of the catchment area.

Ground surface gradients are mainly low, in the order of 0.57 x 10^{-3}, but in places scour channels up to 2 m in depth and 19 m wide have developed in the calcrete and alluvium. Where the calcrete is crossed by the Meekatharra-Wiluna Road the scour channel is known as West Creek, but this watercourse dissipates southeastwards into a massive calcrete area adjoining Lake Way.

Groundwater is present everywhere in the sub-basin, but is freshest in the northern Proterozoic outcrop areas, where salinity ranges from 430 to 2,000 ppm TDS. The groundwater is at shallowest depth, about 4.3 m below ground level in the calcrete, but is brackish, with salinities ranging from 1,750 ppm TDS at Yandil Woolshed well to 5,500 ppm TDS in a well near Lake Way.

LAKE WAY SUB-BASIN

The area immediately west of Lake Way forms this sub-basin. The catchment area is poorly defined, with most drainage starting at a line of east-west hills which form the sub-basin northern water divide. Rocks of the catchment area are altered Archaean volcanics, which hold potable groundwater at depths of between 9 and 20 m below ground level.

HYDROGEOLOGY OF CALCRETE AT PAROO

The outcrop area of highly cavernous and permeable calcrete is broadest northwest of Paroo Woolshed and narrowest where crossed by the Vermin Proof Fence. The drilling showed that the calcrete occupies a shallow trough overlying Proterozoic shale and siltstone, and which bounds it on the southern side. Alluvium occurs on the northern flank (Figs. 6 and 9).

Bores 2 to 18 were constructed using a Mines Department rotary air-drill, the bore diameter was generally 178 mm, and depths ranged from 12 to 37.5 m. Each hole was completed in shale. This method of drilling did not permit the recognition of true lithologies and section thicknesses, because the drill penetrated the formations very rapidly and tended to pulverize the aquifer material. These shortcomings were mainly overcome by logging the holes with a gamma-ray probe, and later re-drilling some of the sites with a percussion rig which permitted the recovery of relatively true rock samples. Bores 19 to 24 were drilled to 178 mm diameter by percussion rig and depths ranged from 12 to 18.3 m. Bore data are summarized in Table 3.

The upper surface of the calcrete is rubbly and sometimes karstic, but is otherwise a plane surface declining gently southeastward from its high point at bore 18. The surface is permeable because of sink holes and caverns in zones of indurated limestone, and because the calcareous soil developed on the limestone is very porous. Developments of gilgai (crabhole) terrain in the soil also facilitate the access of surface water into the calcrete.

TABLE 3. PAROO DRILLING DATA

Bore No.	Total Depth	Estimated thickness of calcrete*	Estimated thickness of permeable, saturated calcrete*
	m	m	m
2	15·8	12	4
3	36·6	3	3
5	22·3	7·6	3·6
6	30·5	11·6	4·6
7	17·0	10·7	4·9
8	15·0	9·1	5·5
9	37·5	3	0
10	22·6	0	0
11	12·0	0	0
12	30·5	9·1	3·3
13	30·5	10·4	4
14	21·3	10·7	4·6
15	27·4	11	4·6
16	15·0	7·3	3·3
17	18·3	9·1	4·6
18	14.3	11	6·1
19	12·0	0	0
20	15·0	11	1·5
21	12·0	0	0
22	18·3	9·1	0
23	18·3	3	0
24	12·0	0	0

* From lithology and gamma-ray logs.

The subsurface lithology of the calcrete is variable, being made up of hard limestone near the surface, opaline silica at about the water table, and friable calcareous material, with odd bands of detrital clay, silt and sand below the silica zone. The bands of opaline silica are massive and up to 1 m thick, but have fissures and cavities in places where fracturing has occurred. Caverns and inter-connecting conduits have also developed in the calcareous material below the silica zone as a result of groundwater circulation. Some caverns communicate by fissures with the surface sinkholes.

Towards its base the calcrete becomes silty and much less permeable. The limestone material normally permits boreholes to stand up uncased.

The calcrete thickness is fairly uniform at between 7.6 and 11.6 m and the average saturated thickness is 4.46 m (Fig. 9).

GROUNDWATER RESOURCES

The groundwater resources of the calcrete are evaluated from bore pumping test data. The results of tests performed on nine bores, in 1969, using a low capacity centrifugal pump, have been reported previously (Sanders, 1971).

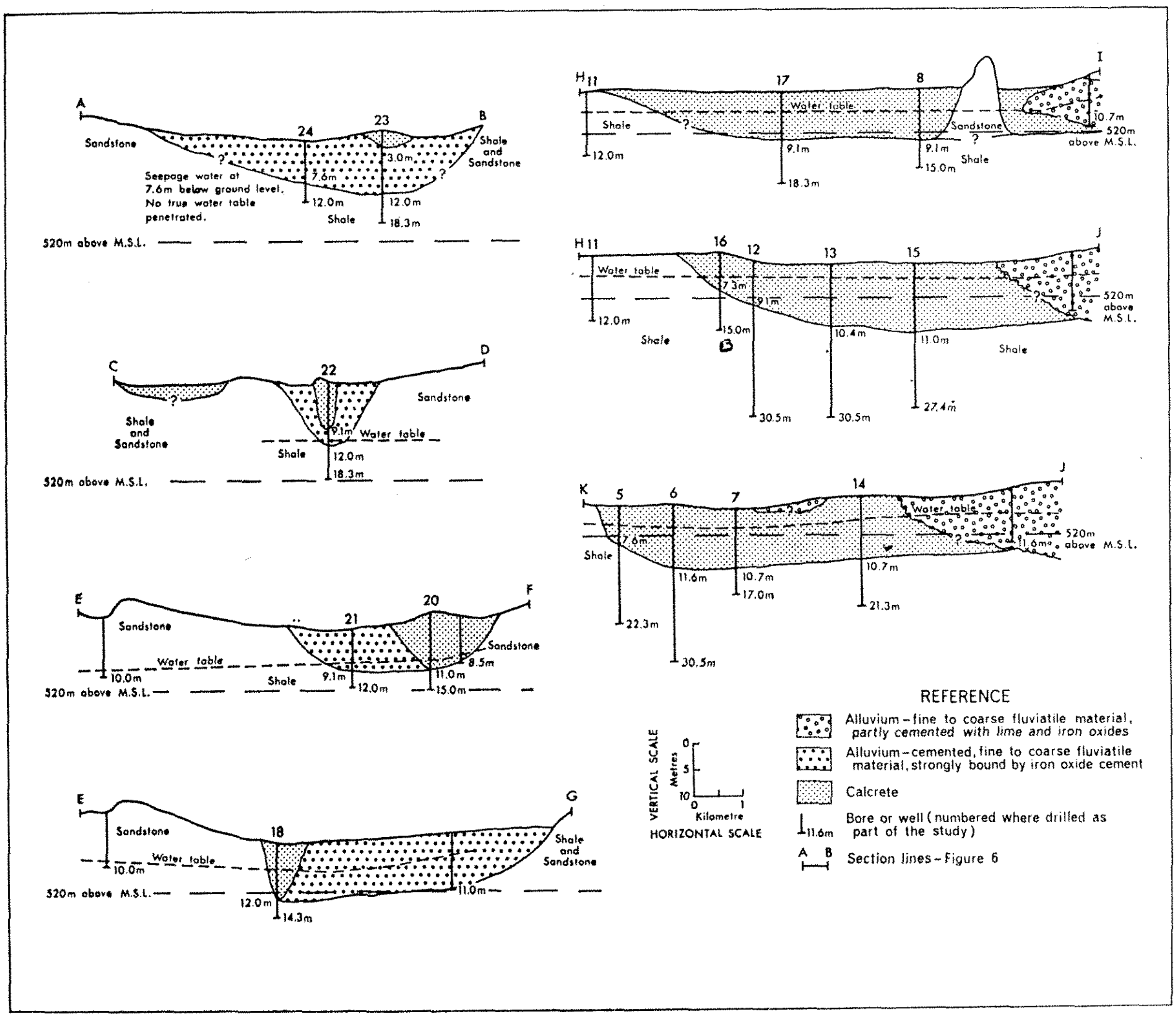


Figure 9. Paroo Station project, Wiluna. Diagrammatic cross sections, Paroo calcrete aquifer.

In late 1971, three bores, 6, 15 and 17, were re-tested using a turbine pump capable of yielding up to 3.3 x 10^3 m^3 of water per day. The bores were selected because they penetrated calcrete which apparently exhibits differing aquifer characteristics, owing to localized aquifer inhomogeneities. Bore 6 is sited in permeable, relatively homogeneous calcrete near the outlet of the Paroo Sub-basin; bore 15 is located in cavernous calcrete, where the borehole and associated observation wells intersect small cavities and conduits; bore 17 is sited in massive limestone, penetrating about 7.6 m of cemented calcrete, and 1.5 m of loosely bound fluviatile sand and gravel. A band of opaline silica occurs just below the water table in the pumped bore at site 17, but not in the observation wells. Relevant test data are listed in Table 4.

TABLE 4. PAROO SUB-BASIN CALCRETE PUMPING TEST RESULTS

Bore No.	Duration time days	Yield m^3 per day	Maximum drawdown in observation well, metres		Salinity pumped water ppm TDS (conductivity)
			r = 7·6 m A	r = 15·2 m B	
6	16·0	3·06 x 10^3	0·415	0·357	1,010
15	5·05	3·29 x 10^3*	0·019	0·019	780
17	3·9	1·20 x 10^3	0·104	0·1006	710
	8·0	0·875 x 10^3	0·083	0·079	710

* Indicates pump capacity rather than potential bore yield at time of pumping test.

Formation Parameters

The formation parameters, transmissivity, specific yield and aquifer anisotropy were calculated from analyses of the various observation well time-drawdown data using standard type curve matching procedures, and from other graphical methods.

For bore 6 the time-drawdown data were analysed using a procedure established by Boulton (1963), which permits the effects of delayed yield from aquifer storage to be taken into account in calculating the aquifer parameters. A method devised by Stallman (1965) which allows for the effects of aquifer anisotropy to be recognized, was also used. These methods gave comparable results for the data from observation well B, but the time-drawdown data from observation well A could not be fitted to the Stallman curves (Table 5). An analysis was also done by the Thiem (1906) method, which is a basic mathematical solution for steady radial groundwater flow, and this gave similar values for transmissivity and specific yield. The mean rounded value for transmissivity at the test site by the three methods is 5,700 $m^3/d/m$ and the average value for specific yield is 0.26.

Bore 15 was a high capacity bore with little drawdown being recorded in either the pumped bore or the associated observation wells. The time-drawdown data for this test could not be satisfactorily analysed as the data curves were strongly distorted, due to the effects of preferential groundwater flow through interconnecting conduits leading toward the pumping bore. An order of transmissivity between 15,000 and 20,000 $m^3/d/m$ was indicated however, but the calculated specific yields are all invalid. A Thiem distance-drawdown analysis could not be done because the slope of the semi-logarithmic plot was too flat to be realistically appraised. Residual drawdown analysis of the observation well recovery data does however, give comparable results for transmissivity, and the rounded average for the test site by this method is 18,800 $m^3/d/m$.

TABLE 5. PAROO SUB-BASIN

CALCRETE Aquifier Parameters (derived by various analytical techniques from pumping test data from Bores 6, 15 and 17†)

Bore No.		6		15		17	
Observation Well		A	B	A	B	A	B
Method of aquifier analysis parameter*							
Boulton	T	5,690	5,690	....	....	....	....
	Sy	0·29	2·27	....	....	....	....
Stallman	T	....	5,720	....	....	5,620	5,300
	Sy	....	0·26	....	....	0·27	0·21
Thiem	T	5,650					
	S	0·22					
Residual drawdown (from recovery data)	T	....	....	17,800	19,700	6,280	6,280

* Transmissivity (T) $m^3/d/m = m^2/d$ Sy = specific yield.

† Pumping tests were carried out using British units of measure, and the analyses were done using these units, but have been metricated to meet the requirements of this report. Graphical plots of the tests are held in the library of the Geological Survey of Western Australia.

The calculated specific yields for Bore 15, by being invalid suggest that the aquifer conditions at the test site are not ideal, and are not adequately represented by the various mathematical assumptions used in normal aquifer analysis. The calcrete at the test site was cavernous and fissured, and of high secondary porosity.

Similar analytical problems were encountered with the time-drawdown data from the two pumping tests at site 17. Strongly distorted, observation well plots resulted from the 3.9 day test at 1.20 x 10^3 m^3/d of water. The second test of 8 days duration pumped at 0.875 x 10^3 m^3/d gave observation well time-drawdown curves which could be matched to a Stallman type curve for a partially penetrating pump bore and observation well, influenced by aquifer anisotropy. No other type curve solution would fit the data. All the bores at site 17 had been constructed and screened to fully penetrate the aquifer, but where an aquifer has intercalated layers of differing hydraulic coductivity, these may cause a marked change in the shape of the pumping response curve and this appears to be the case at site 17.

The cemented calcrete and bands of opaline silica at about 7.6 m level in the pumped bore may have induced the partial penetration effect. The low vertical hydraulic conductivity compared to the radial value (Table 5) indicates that the aquifer is strongly anisotropic.

Residual drawdown analysis of recovery data from observation wells gave transmissivities somewhat higher that those derived by the Stallman method. The mean value of 5,900 $m^3/d/m$ is accepted here as it compares favourably with the transmissivity at site 6.

The average specific yield value of 0.24 at site 17 as calculated by the Stallman method is accepted, as no other values were found to be valid or convincing.

The results of the pumping tests showed variable aquifer conditions through the calcrete, suggesting the need for an average to be struck for the formation parameters before they could be applied to calculating groundwater storage and discharge. Some parts of the calcrete were shown to be exceptionally permeable and porous (e.g. site 15), while other parts were indicated during drilling to be silty and of low permeability and low transmissivity (e.g. bores 12 and 13, Sanders, 1971, Plate 4). Geological mapping of the calcrete indicates that these areas are of generally equal extent and therefore averaging the aquifer parameters should be reasonable.

A transmissivity of 5,800 $m^3/d/m$, averaged from the tests on bores 6 and 17, and a specific yield 0.26 have been adopted for the whole calcrete aquifer. A transmissivity value of 6,320 $m^3/d/m$ and specific yield of 0.3 were adopted in the 1971 report.

Pumping tests at low rates were conducted on three bores (19, 20 and 22), northwest of the explored calcrete, to determine aquifer conditions. Bore cuttings and preliminary water tests during drilling had already indicated that permeabilities in this area were low. The alluvial and colluvial material is strongly bound by lime and iron oxide cements, and the calcrete where it occurs is mainly recemented with carbonate. The calculated transmissivities are low (Table 6), and specific yields could not be determined from the tests. The test on bore 22 was unreliable.

TABLE 6. AQUIFER PARAMETERS BORE 19 AND 20

Bore No.	Duration Time days	Yield metres³ per day	Transmissivity metres³ per day per metre
19	0·3	17·45	0·816
20	2·0	338·1	1,230

These results indicate that the groundwater in this area moves very slowly and is of little recharge value to the calcrete farther down valley, and of no supply potential.

Discharge—Recharge regime

The discharge-recharge regime is governed by groundwater movement as indicated by the potentiometric surface and salinity pattern, and by rainfall over the catchment area. The potentiometric surface of the aquifer was found from survey levelling, and is represented on Figure 6 as hydraulic contours. The direction of groundwater movement is normal to the hydraulic contours and is toward the southeast. The gradient on the water surface is fairly constant at 0.12 x 10^{-3} over the broader part of the calcrete increasing to 0.57 x 10^{-3} near the discharge section at the Vermin Proof Fence.

Discharge

The groundwater in the calcrete is in dyanamic equilibrium with the physical environment, it moves slowly through the aquifer down-gradient to be ultimately evaporated from the terminal salt lake, and it is replenished by rainfall over the catchment area infiltrating to the water table. Other forms of discharge are operating, mainly evapotranspiration and discharge into the poorly permeable rocks surrounding the aquifer. Evapotranspiration is probably considerable but its effects have not been directly measured as a detailed vegetation and land-use survey would be required. Also, as vegetation is relatively sparse over calcrete, and the water table is deeper than 4 m, except where the calcrete is deeply channelled, evapotranspiration would be minor compared with natural underflow and discharge down-gradient.

Subsurface discharge from the calcrete is calculated from transmissivity values found for bores on a cross section at right angles to the direction of groundwater flow.

The computation for underflow follows Darcy's Law (1856) which states that laminar (viscous) flow of water through sand is proportional to the hydraulic gradient, and may be expressed as:

$$Q/A = -K\ dh/dl.$$

where Q = discharge.
A = cross-sectional area.
K = hydraulic conductivity.
dh/dl = hydraulic gradient (G).

For groundwater aquifers the law may be expressed in the simplified form: Q = T (transmissivity) x W (width of section) x G.

The underflow discharge from the calcrete is regarded as an ideal optimum yield for the aquifer, as abstraction of groundwater at a rate equivalent to underflow will subsequently overwhelm discharge past the point of withdrawal, thus utilizing water which is otherwise lost, and should not in the long term reduce the volume of water held in aquifer storage. However during the process of pumpage depletion of part of the groundwater storage will occur before a new equilibrium or water balance can be established, and this may take considerable time.

Two discharge sections have been selected for the calculation of underflow through the aquifer. Section 1 is through bores 17 and 8, and is 6,000 m in length. The hydraulic gradient across the section is 0.12×10^{-3}. Section 2 is near the calcrete outlet, and passes through bore 6. The length of this section is 3,000 m and the gradient 0.57×10^{-3}. Transmissivity for the sections has been adopted at 5,800 $m^3/d/m$.

Q underflow	=	$T \times W \times G$ m^3/d
Section 1	=	$5{,}800 \times 6{,}000 \times 0.00012$
Underflow	=	4,180 m^3/d
Section 2	=	$5{,}800 \times 3{,}000 \times 0.00057$.
Underflow	=	9,920 m^3/d

The difference of 5,740 m^3/d between the two discharge values is considered to be the volume of recharge to the area between the two cross sections, and this must come mainly from rainfall onto the calcrete and surface runoff from the immediate alluvial catchment areas to the north (Figs. 5 and 6).

In arid zone groundwater basins the volume of discharge past the outlet of the basin may be regarded in the long term as about equal to the long term recharge to the system. Hence a mean discharge for the Paroo calcrete of 9,920 m^3/d, equivalent to 3.62×10^6 m^3/year would, over a number of years, essentially equal recharge. The gradient on the water table used for the calculation was a minimal value, arrived at after mapping the hydraulic surface at a time of severe drought when groundwater levels were lowest, and consequently the underflow discharge may be conservative.

The water level in the Paroo bores has been monitored since June, 1969, and over the 2-year period June, 1969 to late May, 1971 the water level in bores has fallen an average of 0.384 m. There has been severe drought in the Wiluna district since mid-1968, with the total rainfall at Wiluna over the period June, 1969 to June, 1971 being 212 mm; the average rainfall for the past 10 years for a similar June to June 2-year period is approximately 498 mm. Such precipitation as has occurred during the drought has usually been from intermittent storms of mainly low intensity, lasting less than 24 hours resulting in little recharge to the aquifer. Average rainfall at Yandil Station near Paroo is reported by Chapman (1962) as being somewhat less than at Wiluna. Under these conditions it is reasonable to expect a steady decline in the groundwater level.

The water table depression over the 90 km^2 of calcrete, represents loss from storage for the 2-year period, taking the aquifer specific yield as 0.26, of:

$$90\ (1{,}000)^2 \times 0.384 \times 0.26\ m^3 = 8.99 \times 10^6\ m^3 \text{ (rounded)}$$

If it is assumed that no effective recharge to the calcrete system has taken place over the 2-year period then the volume of water lost would be mainly due to outflow down-gradient evapotranspiration and lateral discharge into the basement rocks about the calcrete. Normal outflow from the calcrete for the 2-year period would be about 7.24×10^6 m^3 ($2 \times 3.62 \times 10^6$ m^3/year), which leaves a loss of 1.75×10^6 m^3 ($8.99 \times 10^6 - 7.24 \times 10^6$ m^3), which may be attributed to evapotranspiration and discharge into confining rocks at the margins of the calcrete. On an annual basis these losses represent 0.87×10^6 m^3 of water which may be added to the normal yearly discharge of 3.62×10^6 m^3 to give an estimated total discharge or water loss from the calcrete of 4.49×10^6 m^3/year.

This latter maximized loss from the calcrete should also be the equivalent to the long-term recharge, indicating that a potential pumpage of this order should not greatly affect groundwater held in aquifer storage.

Recharge

Groundwater replenishment in the Wiluna district occurs entirely from rainfall and mainly during major storms. The frequency of occurrence of such storms is of importance in understanding the water balance of the district. Chapman (1962, p. 6-9) analysed various frequencies of storm events for the Wiluna area, and these have been summarized and discussed in the interim report on the Paroo calcrete (Sanders, 1971).

The mean annual rainfall at Paroo is about 200 mm, with a storm rainfall of 76 mm having the probability of occurrance of once in 2 years, or 119 mm occurring once in 5 years. The quantity of rainfall required to cause runoff depends on the dryness of the catchment and on the intensity of the rainfall. Local people consider that at least 50 mm are required before creeks in the Paroo area flow, although much of the runoff is by sheet flooding. Infiltration is very rapid into the calcrete but is considerably slower into the hard pan covering the alluvial sediments. Most recharge occurs after runoff from the catchment areas which inundates the calcrete.

In mid-June, 1971 an unusual 8-day storm depression brought 75 mm of rain to Wiluna, and about the same amount of precipitation to the surrounding district. By September, 1971 the water level in the Paroo bores had completely recovered and in some bores the water had risen above the maximum of the preceding 2 years. The June, 1971 storm rain of about 75 mm over the catchment area of 2,300 km^2 was sufficient to replace the 8.99×10^6 m^3 of groundwater depleted during the drought. This represents recharge to the calcrete of 5.2 per cent of the rainfall over the whole catchment. The calculation ignores infiltration into the rest of the catchment and only takes account of water which recharged the calcrete up to September, 1971. As refilling probably continued for a considerable time after this date the percentage value for the storm is probably of the right order but is not conclusive.

Expressed in another way the natural annual groundwater loss from the calcrete of 4.49×10^6 m^3/ year, represents a recharge coefficient of 0.98 per cent of an adopted annual catchment rainfall of 200 mm over the total 2,300 km^2 catchment. These percentage differences indicate that most recharge follows the higher storm rainfalls.

Runoff past the outlet of the Paroo Sub-basin only occurs after precipitation equivalent to the once in 5 years storm event of about 119 mm. This can result in flow along the deep erosion channel in calcrete on Yandil Station, and eventually, when added to the runoff from the Yandil catchment area, may cause flow along West Creek (Fig. 5).

Salinity Pattern

Isohalsine plots of the calcrete have been made and discussed previously (Sanders, 1971, Plate 5). They show that groundwater salinity increases gradually from north to south across the aquifer; the least saline water being in the tributary alluvial areas, as indicated by bore and well salinities shown on Figure 5. The plots indicate recharge from the northern alluvial zones. A broad area of fair quality water about bore 17 indicates direct infiltration of rainfall, and intake of water dumped on the cavernous part of the calcrete after runoff from the catchment.

Stored Water

The volume of stored water in the calcrete may be calculated by applying the accepted aquifer specific yield of 0.26 over 90 km^2 of aquifer having an average saturated thickness of 4.46 m.

$$\text{Volume} = \text{Area} \times \text{aquifer thickness} \times \text{specific yield}$$
$$= 90\ (1{,}000)^2 \times 4.46 \times 0.26\ m^3$$
$$\text{Volume (rounded)} = 104.4 \times 10^6\ m^3$$

This is sufficient stored water to permit pumpage well in excess of normal discharge, if this is considered desirable, and to permit continued abstraction over long periods of drought. Mining of the groundwater at a rate greater than it may be replaced during infrequent flood events is not advisable as a conserved perpetuating resource would be the most sensible management.

Hydrochemistry

Recharge to the calcrete is entirely from rainfall. Dissolved solids in the groundwater are derived from the rain, the aquifer and its catchment, and cotamination from the surface.

Standard chemical analyses of Paroo groundwater were carried out by the Government Chemical Laboratories and are reported elsewhere. Over the calcrete the total salinities range from 710 ppm to 1,330 ppm TDS, but the salinity profile in each borehole varied little for the full thickness of the aquifer. The total salt content is within the upper limit of potability of 1,500 ppm as set for Western Australia by the Public Works Department. Also the concentration of most individual ions is within accepted limits, except for the nitrate and fluoride ion concentrations.

The nitrate concentration in the groundwater is high, ranging from 34 ppm to 124 ppm, but this is characteristic of most Wiluna district groundwaters (Morgan, 1966). Ingestion of water containing nitrates in excess of 50 ppm is reliably reported as causing infantile methaemoglobinaemia, an illness confined to infants during their first months of life. In Western Australia no incidence of the disease has yet been recorded although groundwater containing high nitrates has been used for domestic consumption since the beginning of the century. In the environment of central Western Australia domestic use of the Paroo groundwater should be satisfactory, but careful watch must be kept for any incidence of anoxia.

The fluoride concentration (0.8 ppm to 2.0 ppm) in Paroo groundwater is higher than recommended for an area where the mean maximum temperature is 29°C. The optimum level of fluoride in drinking water at this temperature is 0.7 ppm (United States Department Public Health, 1962).

The water is also very hard, and although this may not be deleterious to health it does affect pipe lines, boilers, and domestic utensils. The groundwater hardness at Paroo ranges from 330 ppm to 445 ppm $CaCO_3$. Bean (1962) recommends that an ideal quality water should not contain more than 80 ppm $CaCO_3$.

Some groundwater samples were submitted to the State X-ray Laboratories for analysis of radiation in solution. Some degree of radioactivity, up to 70 times background was recorded, but it is not considered to be a health hazard.

HYDROLOGY OF YANDIL SUB-BASIN

Geological mapping of aquifer rocks, and well and bore census work has been done in this sub-basin, but no exploratory drilling. Groundwater is brackish but of good stock quality, and is satisfactory for many industrial uses. Some water was pumped from three wells in calcrete near Lake Way between 1933 and 1946 for use in a gold beneficiation process at the now abandoned Wiluna gold mines (Fig. 5). The volume of water abstracted was never recorded, but the type of pump used at each well was probably capable of pumping 280 m^3/d of water. The wells are no deeper than 9 m, and do not fully penetrate the aquifer. The water level in the wells now stands at 3.9 m below ground level.

GROUNDWATER RESOURCES

Most groundwater is available from the three calcreted areas within the central drainage depression. The largest of these calcretes adjoins Lake Way and has an areal extent of 35 km^2. The true thickness of the rock is not known, but from census information and from some recent diamond drill-holes put down for nickel search, a thickness of at least 15 m is indicated. The calcrete overlies Archaean ultramafic rocks which are of interest as possible host rocks to nickel mineralization, and consequently much of the calcrete is pegged for mineral claims.

The near-surface groundwater ranges in salinity from 4,400 ppm to 5,500 ppm TDS, but the water at depth in the aquifer is probably more saline, particularly near Lake Way. Examination of the Mine wells shows that the calcrete is massive with recent carbonate growth sealing many of the older waterworn flow channels. Much of the primary porosity has been lost and even some of the secondary porosity greatly reduced. This has caused a considerable loss in permeability and reduction in aquifer specific yield. The same effects have been noted by the author in the Lake Violet Basin calcrete southeast of Wiluna, where recent tests indicate a transmissivity of 660 m^3/d/m and specific yield of 0.05.

If the Lake Way calcrete has a specific yield of about 0.05 and has an assumed average saturated thickness of 10 m then there would be: $10 \times 0.05 \times 35\ (1{,}000)^2 = 17.5 \times 10^6\ m^3$ of water held in aquifer storage. These conclusions are subjective and it is recommended that the hydrology of the Yandil Sub-basin be the subject of a comprehensive programme of investigation in order to place discharge, evapotranspiration and storage estimates on a firm basis prior to instituting any scheme for groundwater abstraction.

The smallest area of calcrete in the Yandil Sub-basin is near Bubble Well and has an indicated extent of 15 km^2. The calcrete is vegetated along the channel of West Creek by large stands of river gum trees. The watercourse is up to 2 m deep and 19 m wide but flow is intermittent and probably only occurs as a result of very heavy rainstorms permitting the overtopping of the calcrete aquifers farther upstream.

The area is a local scenic spot and picnic ground and its conservation is recommended.

The calcrete aquifer on Yandil Station immediately southeast of Paroo, has an area of 30 km^2, the contained groundwater ranging in salinity from 1,540 to 4,550 ppm TDS, and is generally at a depth of 4 m below ground level. Much of the water is derived as underflow from the Paroo calcrete.

The volume of water held in storage in this aquifer is estimated by assuming the specific yield to be 0.26 and the average saturated thickness 5 m, as indicated from the well census; storage is then: $30\ (1{,}000)^2 \times 0.26 \times 5 = 39 \times 10^6\ m^3$, part of which could be abstracted for industrial use.

An approximate estimate of the groundwater discharge from the Yandil Sub-basin can be derived by assuming a transmissivity of 660 m^3/d/m and applying it to a 6,000 m cross section near Garden Well where the hydraulic gradient is 1.9×10^{-3}. The estimated underflow towards Lake Way is then 2.7×10^6 m^3/year. However, 3.62×10^6 m^3/year is supplied to the Yandil Sub-basin groundwater storage as underflow from the Paroo calcrete, and probably another 5.8×10^6 m^3/year is added through infiltration of rainfall over the Yandil catchment reaching the water table. This latter value is derived by taking the Paroo discharge as equivalent to 0.98 per cent of the mean annual rainfall over the full Paroo catchment area, and applying that percentage as a recharge coefficient for the Yandil catchment. The total annual groundwater inflow to the Yandil system is then of the order of 9.4×10^6 m^3, but outflow is only 2.7×10^6 m^3/year. Clearly a substantial volume of water appears to be lost from the system and this is attributed to evapotranspiration.

Much of the 260 km^2 calcrete and alluvial terrain in the Yandil Sub-basin is vegetated by river eucalypts which have their roots in water. Forestry officers report that these trees transpire very large volumes of water annually, and could easily account for annual groundwater losses of about 6.7×10^6 m^3.

CONCLUSIONS

Analysis of drilling and pump testing data from the 90 km^2 calcrete aquifer on Paroo Station has indicated that up to 3.62×10^6 m^3/year of potable water is discharged past the outlet of the sub-basin. Indirect measurements of evapotranspiration and groundwater discharge into the confining rocks of the calcrete indicate an annual water loss from the aquifer by these means of 0.87 x 10^6 m^3. The total discharge or aquifer loss is then 4.49 x 10^6 m^3/year, which represents 0.98 per cent of the mean annual rainfall of 200 mm falling over the total catchment area of 2,300 km^2.

There are 104.4 x 10^6 m^3 of groundwater held in aquifer storage.

Southeast of the Paroo calcrete are three smaller calcretes all located in the Yandil Sub-basin. Underflow through each of these has not been estimated, but 39 x 10^6 m^3 of brackish water should be stored in the calcrete joining the Paroo system, and 17.2 x 10^6 m^3 of poorer quality water stored in the adjacent calcrete to Lake Way. Storage within the smallest calcrete has not been estimated, as it is considered to be an area worthy of groundwater conservation. Annual rainfall recharge to the Yandil Sub-basin could be at least 5.8 x 10^6 m^3. Discharge into Lake Way is possibly only about 2.7 x 10^6 m^3/year which indicates that substantial groundwater reserves are lost from the system annually. These losses are attributed to evapotranspiration.

Uranium and thorium enrichment has been noted in the Wiluna district and other calcretes, and exploration for these elements is encouraged, although government agencies should be aware of the possible clash of interests between mineral mining and groundwater exploitation.

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STRATIGRAPHIC NOMENCLATURE OF CRETACEOUS ROCKS IN THE PERTH BASIN

by A. E. Cockbain and P. E. Playford

ABSTRACT

An intra-Neocomian unconformity separates the Middle Jurassic to early Neocomian Yarragadee Formation from the overlying Cretaceous rocks, most of which are placed in the Warnbro and Coolyena Groups. The Early Cretaceous Warnbro Group consists of the South Perth Shale (with basal Gage Sandstone Member), Leederville Formation and Dandaragan Sandstone, and is a mixed marine and continental clastic sequence. The disconformably overlying Coolyena Group comprises (in ascending order) the Osborne Formation, Molecap Greensand, Gingin Chalk and Poison Hill Greensand and is a marine glauconite-bearing sequence of Albian to Late Cretaceous age. The Bullsbrook Beds, Donnybrook Sandstone and Maxicar Beds are probably correlatives of the Warnbro Group and the Lancelin Beds correlate with the upper part of the group. The Bunbury Basalt is a flow deposited on the unconformity surface of the Yarragadee Formation.

INTRODUCTION

Regional mapping by the Geological Survey and exploration for hydrocarbons by West Australian Petroleum Pty. Ltd. (Wapet) have resulted in a better understanding of the Cretaceous rocks in the Perth Basin. This, in turn, has necessitated a revision of the stratigraphic nomenclature, and the purpose of this paper is to formalize this revision and concisely describe the units.

The revised stratigraphic nomenclature may be summarized as follows (Fig. 10):

Main sequence		Probable equivalents
Coolyena Group (Albian-Senonian)	Poison Hill Greensand Gingin Chalk Molecap Greensand Osborne Formation	Lancelin Beds
	DISCONFORMITY	
Warnbro Group (Neocomian-Aptian)	Dandaragan Sandstone Leederville Formation South Perth Shale	Bullsbrook Beds, Donnybrook Sandstone and Maxicar Beds
	UNCONFORMITY	
(Middle Jurassic-Neocomian)	Yarragadee Formation	

Cretaceous sediments are exposed at the surface over a wide area of the Perth Basin, although outcrops are generally poor. An important unconformity occurs in the Neocomian sequence; Lower Neocomian, Upper and Middle Jurassic rocks below the unconformity are placed in the Yarragadee Formation whilst most of the Cretaceous sequence above the unconformity is placed in the Warnbro and Coolyena Groups. The Cretaceous part of the Yarragadee Formation has a maximum known thickness of 1,500 m and the overlying Cretaceous rocks exceed 1,600 m in thickness.

YARRAGADEE FORMATION

The Yarragadee Formation ("Yarragadee Beds" of Fairbridge, 1953, amended Playford, Willmott, and McKeellar, *in* McWhae and others, 1958), ranges in age from Middle Jurassic to Early Cretaceous; only the Cretaceous portion will be discussed here. Neocomian strata placed in the Yarragadee Formation occur in the Dandaragan Trough and Vlaming Sub-basin, the thickest development being offshore. The rocks consist predominantly of sandstone and siltstone and are

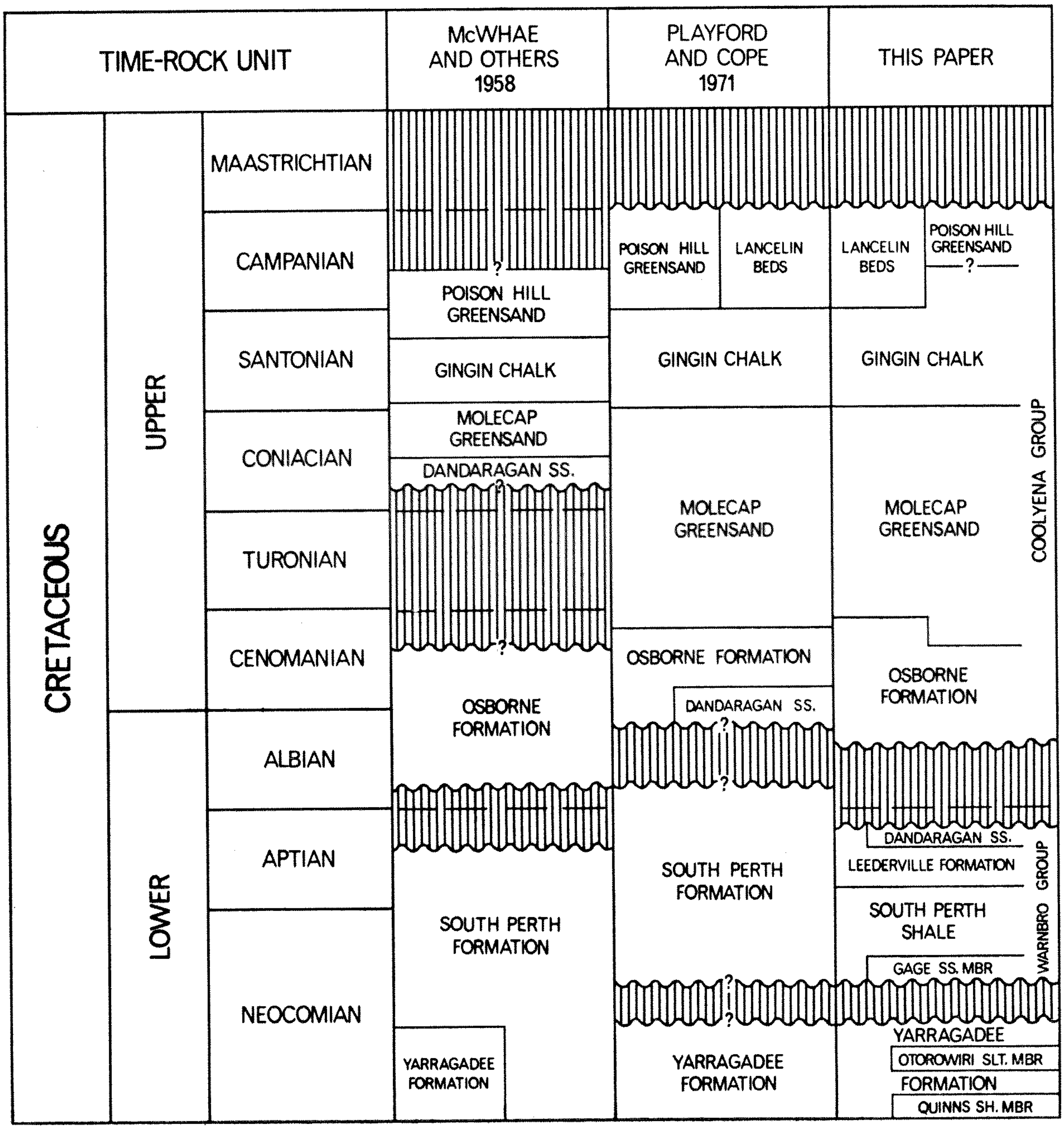

Figure 10. Cretaceous stratigraphic nomenclature, Perth Basin.

mainly continental onshore and partly marine offshore. Two members are recognized in the Neocomian part of the Yarragadee Formation, the Quinns Shale Member and the Otorowiri Siltstone Member.

The name *Quinns Shale Member* (Bozanic, 1969) has been used by Wapet geologists for a well-defined shale unit in the Yarragadee Formation in offshore wells in the central Perth Basin. The type section is between 1,590 m and 1,647 m in Quinns Rock No. 1 well (lat. 31° 48′ 08″S long. 115° 30′ 50″E). The member occurs in offshore wells between Quinns Rock No. 1 in the north and Sugarloaf No. 1 in the south and is a good seismic reflector. The microflora suggests that the Quinns Shale Member is a lagoonal deposit of earliest Neocomian age. The base of the member is taken to mark the Jurassic-Cretaceous boundary in the Perth Basin.

The *Otorowiri Siltstone Member* of Ingram (1967) is recognized in some of the Arrowsmith River water bores, west of Arrino in the northern Dandaragan Trough. The type section is in Arrowsmith River No. 25 bore between 253 m and 277 m (lat. 29° 33′ 15″S, long. 115° 32′ 00″E). The maximum known thickness is 37 m. The member consists predominantly of siltstone. It contains a rich assemblage of Early Cretaceous plant micro fossils, including microplankton, together with reworked forms of Devonian, Permian, Triassic and Jurassic age. The member is correlated on microfloral evidence with a group of shales in the Neocomian part of the Yarragadee Formation in offshore wells (A. Williams, pers. comm., 1972).

WARNBRO GROUP

The Warnbro Group is proposed herein for the South Perth Shale, Leederville Formation, and Dandaragan Sandstone. Warnbro No. 1 well between 1,003 m and 2,204 m is taken as the reference section for the group. The Warnbro Group includes the mixed marine and continental clastic sediments laid down during the Early Cretaceous transgression of the Perth Basin.

South Perth Shale (Fairbridge, 1953). The South Perth Shale is a shallow marine to continental sequence of interbedded shale and siltstone with minor sandstone. Calcareous beds, grading to limestone, are present in some areas. Sandstone is especially common at the base. The type section is in the South Perth No. 1 water bore (lat. 31° 58′ 31″S, long. 115° 50′ 57″E) between 497 m and 567 m (total depth). In the nearby South Perth No. 2 water bore the formation is overlain by the Leederville Formation. Neither well penetrated the underlying Upper Jurassic part of the Yarragadee Formation, which is known to occur below the South Perth Shale in other Perth Metropolitan water bores. In offshore wells Yarragadee Formation of Neocomian age underlies the South Perth Shale, and seismic work has shown that a major unconformity separates the two formations.

McWhae and others (1958) considered that it was impossible to separate the South Perth Shale from the Leederville Formation and combined the two formations under the name "South Perth Formation". However, subsequent work has shown that the two formations can be recognized, although the boundary between them is generally transitional.

The formation is best known in the subsurface and is not known to crop out with certainty. The South Perth Shale is well developed offshore in the Vlaming Sub-basin. It is 795 m thick in Warnbro No. 1 well and is probably even thicker farther west. Onshore the formation is virtually confined to the Perth Metropolitan area.

Early Cretaceous foraminiferal and microplankton assemblages are present in the formation (Coleman, 1952; Cookson and Eisenack, 1958). The microflora is referred to Balme's (1964) *Microcachyridites* assemblage, which is now thought to be predominantly of Early Cretaceous age (B. E. Balme, pers. comm., 1969).

In many wells and water bores the base of the South Perth Shale is sandy, as would be expected in the initial stages of a marine transgressive sequence. In offshore wells the basal sandstone has been named the *Gage Sandstone Member* (Bozanic, 1969). The type section is in Gage Roads No. 1 well (lat. 31° 57′ 12″ S, long. 115° 22′ 38″ E) between 1,588 m and 1,801 m, a thickness of 213 m. The unit consists of fine-grained to conglomeratic sandstone with minor siltstone and shale, and appears to have a near-shore marine origin. The Gage Sandstone Member has a known maximum thickness of 259 m (in Warnbro No. 1 well) and it yielded small but encouraging amounts of oil in Gage Roads No. 1 well.

Leederville Formation ("Leederville Sandstone" of Fairbridge, 1953). The Leederville Formation is a sequence of sandstone, frequently feldspathic and occasionally glauconitic, and conglomerate with siltstone and claystone. Sandstone predominates in some sections, but in others (including the type section) it is not the major constituent and for this reason the name of the unit is herein amended to Leederville Formation.

The type section is between 198 m and 433 m in the Leederville Valley water bore (lat. 31° 56′ 05″ S, long. 115° 49′ 58″ E) (Pudovskis, 1962), a total thickness of 235 m. The formation is overlain, probably unconformably, by the Kings Park Shale and rests, apparently conformably, on the South Perth Shale in the type section. The Leederville Formation is overlain by the Osborne Formation in part of the Perth Metropolitan area; the contact is probably disconformable, palynological evidence suggesting a short time break (B. S. Ingram, pers. comm., 1969).

The Leederville Formation is well developed in the subsurface of the Perth region, where it is about 250 m thick. Offshore it thickens to a known maximum thickness of 545 m (in Gage Roads No. 1 well). The Leederville Formation overlaps the underlying South Perth Shale both north and south of Perth and rests directly on the Yarragadee Formation. In Sugarloaf No. 1 well, the Leederville Formation rests on Neocomian Yarragadee Formation (Bird and Moyes, 1971); in onshore wells south of Pinjarra, the Leederville Formation unconformably overlies the Yarragadee and older formations.

The "Strathalbyn Sandstone", "Moochamullah Sandstone" (Playford and Willmott, 1958) and "Quindalup Beds" (Lowry, 1967) are now included in the Leederville Formation. In the Agaton water bores the formation was previously referred to as the "marine member of the South Perth Formation" (Passmore, 1969). Other possible correlatives of the Leederville Formation are the Dandaragan Sandstone, Bullsbrook Beds, Donnybrook Sandstone and Maxicar Beds.

Onshore the Leederville Formation is usually of continental facies and is unfossiliferous. However, in the Agaton area and in Sugarloaf No. 1 well it is marine and is of Neocomian-Aptian age according to the contained microplankton.

Dandaragan Sandstone ("Dandaragan Series", Blatchford, 1912 (lower part only); amended, Fairbridge, 1953). The Dandaragan Sandstone is a unit of massive to thickly bedded, ferruginous, feldspathic, medium to coarse-grained sandstone. It overlies the Yarragadee Formation with angular unconformity and is overlain with apparent conformity by the Molecap Greensand, although this contact is probably disconformable. The type section of the formation is 6 km west of Dandaragan (lat. 30° 41′ 30″ S, long. 115° 38′ 30″E).

The Dandaragan Sandsone is exposed discontinuously between Badgingarra and Gingin. The type section is 33 m thick and is the thickest section measured to date. No fossils have been found in the formation other than fossil wood. It is believed to be of Early Cretaceous age because of its stratigraphic position, and to correlate possibly with the upper part of the Leederville Formation.

Bullsbrook Beds (Walkom, 1944). The Bullsbrook Beds are an interbedded sequence of poorly sorted sandstone and siltstone overlying Precambrian granitic rocks. The type section is at lat. 31° 39′ 53″ S, long. 116° 02′ 40″ E to the east of Bullsbrook. The Bullsbrook Beds are known only from the type area east of the Darling Fault where they are probably overlain by the Osborne Formation, although the contact is not exposed. Exposures to the west of the Darling Fault, previously mapped as Bullsbrook Beds (Low and Lake, 1970) are now assigned to the Osborne Formation. The unit was laid down in a valley incised into the Darling Scarp, probably during Early Cretacious times, post-dating the last important period of movement along the Darling Fault.

Walkom (1944) reported the occurrence of fossil plants, including *Cladophlebis, Thinnfeldia* and *Elatocladus*, in the Bullsbrook Beds and tentatively suggested an Early Cretaceous age for the unit. It is not possible at present to be sure of the correlation of the Bullsbrook Beds with other Lower Cretaceous units in the Perth Basin, but they may correlate with the Leederville Sandstone.

Donnybrook Sandstone (Saint-Smith, 1912). The Donnybrook Sandstone is composed of yellow, fine to medium-grained feldspathic sandstone, which is generally only crudely bedded. The formation overlies Precambrian granitic rocks, and is overlain by laterite and other Quaternary deposits. The type section proposed by Playford and Willmott (1958) and Lowry (1965), is situated 6 km north of Donnybrook (lat. 33° 31′ 19″S, long. 115° 49′ 48″E). The formation is exposed in a belt 34 km long along the Darling Scarp north and south of Donnybrook. Outliers of the formation also occur 6 km to the east of the Darling Fault near Brookhampton and these rocks were deposited in an ancient valley eroded through the scarp. The thickest known exposure (about 61 m) occurs in this ancient valley; the type section is 40 m thick (Lowry, 1965).

The age of the Donnybrook Sandstone is indefinite but regional correlations suggest that it may be Early Cretaceous. Teichert (1947) reported footprints of a small quadruped from the formation near Brookhampton and he suggested that it might be of Triassic age. Balme (1956) recorded a Cretacous microflora in a sample of carbonaceous siltstone from a shaft near Donnybrook, but this is now believed to be from the Leederville Formation. The Donnybrook Sandstone is probably equivalent to the Maxicar Beds and may correlate also with the Leederville Formation.

Maxicar Beds (Lowry, 1965; Playford and Low, 1972). The Maxicar Beds consist of current-bedded, medium to coarse-grained, feldspathic, ferruginous sandstone. The type section is at lat. 33° 24′ 49″ S, long. 115° 24′ 49″ E and the unit is exposed along the Darling Scarp in the vicinity of Maxicar homestead, about 19 km north of Donnybrook. The total thickness of the unit is unknown, but is at least 9 m.

The stratigraphic relationships of the Maxicar Bads are uncertain. The unit is believed to overlie Precambrian rocks directly, and it is probably laterally equivalent to the Donnybrook Sandstone. The beds were included in that formation by Playford and Willmott (1958).

A species of *Pterotrigonia* from the Maxicar Beds was identified by J. M. Dickins (pers. comm., 1957) and he considered it to be of Jurassic or Cretaceous age. An Early Cretaceous age for the unit now seems most likely on the basis of regional correlations.

COOLYENA GROUP.

The Coolyena Group is proposed herein for the Osborne Formation, Molecap Greensand, Gingin Chalk and Poison Hill Greensand (in ascending order). The name is taken from the Aboriginal name for Molecap Hill near Gingin. The Coolyena Group thus includes the marine glauconite-bearing beds of predominantly Late Cretaceous age occurring in the central part of the Perth Basin, and is separated by a disconformity from the underlying Warnbro Group. The Lancelin Beds correlate with the upper part of the Coolyena Group. The maximum thickness of the group is 450 m in Warnbro No. 1 well.

Osborne Formation (McWhae and others, 1958). The Osborne Formation is a unit of interbedded sandstone (in part calcareous), siltstone, shale and claystone. The formation is characteristically glauconitic and the argillaceous sediments are usually dark grey to black. The formation overlies the Leederville Formation disconformably and is overlain disconformably by the Kings Park Shale in the Perth area. The type section of the formation is in the King Edward Street water bore (lat. 31° 54′ 00″S, long. 115° 49′ 00″E) from 37 m to 134 m.

The relationship between the Osborne Formation and the Molecap Greensand is not known with certainty. It is probable that the Molecap Greensand is equivalent to the uppermost part of the Osborne Formation. The two formations may be in conformable contact in some of the Agaton water bores; however, usually the two formations are not seen together and the Molecap Greensand is considerably thinner than the Osborne Formation and may represent the overlapping portion of the upper part of the Osborne Formation.

The Osborne Formation is known from bores in the Perth Metropolitan area, offshore in Warnbro No. 1, Sugarloaf No. 1 and Quinns Rock No. 1 wells, and extends in the subsurface as far north as Watheroo. Between Perth and Moora the formation also occurs as an outlier east of the Darling Fault. It crops out in the Moore River near Mogumber where the section was informally named the "Mogumber Formation" by Playford and Willmott (1958). The formation ranges from about 60 m to over 200 m in thickness.

The Osborne Formation contains a rich microflora, including microplankton which date it as Albian and Cenomanian (Cookson and Eisenack, 1958).

Molecap Greensand (Fairbridge, 1953). The Molecap Greensand consists of greensand and glauconitic quartz sandstone which rest with probable conformity on the Osborne Formation or disconformably on the Dandaragan Sandstone, and are overlain conformably by the Gingin Chalk. The type section is in the quarry on Molecap Hill near Gingin (lat. 31° 22′ 00″S, long 115° 24′ 00″E). Two well developed phosphatic beds, each about 0.6 m thick, are present at the top and bottom of the formation in the Dandaragan area (Matheson, 1948). The formation is recognized in discontinuous exposures between Badgingarra and Gingin. At the type section the formation is 11 m thick and the average exposed thickness in the Gingin-Dandaragan area is between 10 m and 12 m.

Ichthyosaur and plesiosaur bones have been found in the formation (Teichert and Matheson, 1944), together with a few bivalves and belemnites. Deflandre and Cookson (1955) report Late Cretaceous microplankton from the formation, and this dating has since been confirmed by B. S. Ingram (pers. comm., 1969).

Gingin Chalk (Glauert, 1910). The Gingin Chalk is a unit of white, friable, slightly glauconitic chalk, containing thin beds of greensand in some areas, which rests disconformably on the Dandaragan Sandstone or conformably on the Molecap Greensand, and is overlain conformably by the Poison Hill Greensand. The presence of a thin phosphatic horizon (well developed at Dandaragan, weak at Gingin) at the top of the Molecap Greensand may indicate that there has been a slight hiatus between deposition of the two formations. The type section is in MacIntyre Gully, 1.6 km north of Gingin (lat. 31° 19′ 00″ S, long. 115° 54′ 00″ E).

The Gingin Chalk is exposed in the area between Badgingarra and Gingin. It occurs in the subsurface as far north as Watheroo. The type section is 19 m thick, and the unit is usually about 18 m thick in most areas. The apparent absence of the Gingin Chalk in some places is commonly due to landsliding, but there is evidence that it occasionally pinches out against the disconformity with the Dandaragan Sandstone.

The Gingin Chalk is richly fossiliferous, with a fauna of foraminifers (including the *Globotruncana lapparenti* group and *Rugoglobigerina* spp., Belford, 1960), the pelagic crinoids *Marsupites* and *Uintacrinus* (in the lower 6 m of the type section), abundant *Inoceramus* and other bivalves (Feldtmann, 1963), ammonites of the *Pachydiscus* type, ostracods, echinoids, brachiopods and abundant coccoliths (see further references in McWhae and others, 1958). The fossils indicate a Santonian (middle Senonian) age with the possibility that the upper part of the formation extends into the Campanian.

Poison Hill Greensand (Fairbridge, 1953). The Poison Hill Greensand is composed of greensand and glauconitic sandstone, which is crudely bedded and thick bedded. Exposures are commonly strongly lateritized. The formation rests conformably on the Gingin Chalk, and is overlain by laterite and associated Quaternary deposits. The type section is at Poison Hill near Gingin (lat. 31° 18′ 00″ S, long. 115° 53′ 00″ E). The formation is exposed in a belt from near Badgingarra to south of Gingin, and it also occurs in the subsurface as far north as the Watheroo area. The type section is 37 m thick, and the total maximum thickness of the formation probably exceeds 45 m (Playford and Willmott, 1958).

The Poison Hill Greensand has been dated as Late Cretaceous, based on an assemblage of pollen and microplankton from a shothole sample, but the precise age is in doubt (B. E. Balme, pers. comm, 1969). It is possible that the unit is a facies equivalent of the Campanian Lancelin Beds. Alternatively it may be younger than that unit.

Lancelin Beds (Edgell, 1964). The Lancelin Beds consist of light grey marl which underlies Quaternary sands in the Lancelin No. 2B water bore (lat. 31° 04′ 00″ S, long. 115° 19′ 20″ E). The unit is 14 m thick in this bore, extending from 32 m to 46 m (total depth). The Lancelin Beds are considered to be Campanian in age based on the foraminiferal fauna (especially the presence of *Bolivinoides granulatus* and *Neoflabellina praereticulata;* Edgell, 1964). If the Gingin Chalk is proved to extend into the Campanian, then the term Lancelin Beds can be dropped; however for the present the unit should be retained.

Bunbury Basalt ("Bunbury lava flow" of Saint-Smith, 1912; formally named by McWhae and others, 1958). The Bunbury Basalt is a flow of porphyritic or microporphyritic basalt (Edwards, 1938; Trendall, 1963). The rock is commonly vesicular, shows well developed columnar jointing in some areas and is dark grey to black in colour. Exposures of basalt on the beach at Bunbury may be taken as the type section (lat. 33° 19′ 30″ S, long. 115° 37′ 40″ E).

The Bunbury Basalt in surface exposures is overlain by Coastal Limestone, and the base is not exposed. In the subsurface it is overlain by the Warnbro Group with apparent conformity, and it rests on an erosional surface which is probably the unconformity at the top of the Yarragadee Formation. The basalt crops out in a number of areas from Bunbury to Black Point, extending as far east as the Darling Fault and as far west as the Scott River (Lowry, 1965). The thickest exposed section of the unit is 12 m, situated 1.6 km northeast of Black Point, while the thickest known subsurface section is 85 m, in the Boyanup bore..

Dolerite that intrudes the Sue Coal Measures in Sue No. 1 (J. E. Glover, *in* Williams and Nicholls, 1966) and Blackwood No. 1 wells may be comagmatic with the Bunbury Basalt. The occurrence in Sue No. 1 well has been dated as 136± 3 m.y. (written communication from B. M. R., 1972).

The Bunbury Basalt is believed to be of Early Cretaceous age. B. E. Balme (pers. comm., 1969) now believes on palynological grounds that the sediments immediately above the basalt flow in Abba River No. 3 bore are of Early Cretaceous age, whereas the sediments unconformably below are Late Jurassic. The Bunbury Basalt is thought to represent a single flow which was spread along valleys eroded into the Yarragadee Formation prior to deposition of the Warnbro Group. The vent from which the flow was derived is unknown. This volcanism may have occurred during one of the last periods of movement along the Darling Fault in this area, and is probably related to the rupture of Gondwanaland.

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PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1972

by G. H. Low

ABSTRACT

The tempo of oil exploration activity in Western Australia continued to increase during 1972, especially in the Northwest Shelf area. The B.O.C. group followed up earlier discovery wells on the North Rankin, Angel and Goodwyn fields with five successful extension tests. West Australian Petroleum Pty. Ltd. also was active in this area spudding three new field wildcat wells offshore, and one deeper pool test on Barrow Island, in addition to onshore wells in the Perth, Carnarvon and Canning Basins. Arco Australia Ltd. drilled four new field wildcat wells in the Bonaparte Gulf Basin, and Abrolhos Oil N. L. and Union Oil Development Corporation drilled new field wildcat wells in the northern Perth Basin and southern Perth Basin respectively.

Forty-five wells were drilled during the year and five were drilling at 31st December, for a total of 102,876 m of drilling. Geophysical activity also increased during the year, especially in marine seismic, aeromagnetic and ship-board gravity surveys. Several new petroleum concessions and special licenses were issued during the year.

INTRODUCTION

Petroleum exploration activity in Western Australia has steadily expanded over recent years and the trend continued in 1972. Exploratory drilling increased over the previous year as shown in the following tabulation:

	Wells completed		Wells drilling on 31st December	
	1971	1972	1971	1972
New field wildcat wells	22	22	1	4
Extension test wells	1	6	0	1
Deeper pool test wells	0	0	0	1
Stratigraphic wells	6	16	1	0

Total drilling : 1971— 70,620 m
1972—102,876 m

One of the 1972 wildcat wells (Angel No. 1) made a gas and condensate discovery, and a significant oil discovery was made in another (Eaglehawk No. 1). Successful extension tests of fields discovered in 1971 were made in five wells (Angel No. 2, Goodwyn No. 2 and North Rankin Nos. 2, 3 and 4).

Test figures for gas given in the text are quoted in thousands of cubic metres per day (x 10^3 m^3/d). Oil and condensate test figures are quoted in barrels per day (b/d).

Geophysical survey activity also continued to increase, and surface geological investigations continued at a rate similar to that for 1971. The totals for 1972 are as follows:

Type of Survey	Line km	Party months or Geologist months
Land seismic	3,266	....
Marine seismic	43,218	....
Gravity (land)	....	10·45
Gravity (ship-board)	4,362	....
Aeromagnetic	26,445	....
Magnetic (ship-board)	5,019	....
Geological	....	13

A geochemical survey carried out during the year involved the collection of 265 samples over 106.5 line km.

PETROLEUM TENEMENTS

A number of new petroleum tenements were issued during the year, and the offshore tenement WA-22-P was relinquished by West Australian Petroleum Pty. Ltd. New tenements issued under the Petroleum (Submerged Lands) Act 1967 are in the offshore Bremer and Eucla Basins. New onshore tenements issued under the Petroleum Act 1967 are located in the Bremer, Perth, Carnarvon, Canning, Officer and Eucla Basins.

During 1972 authorities were granted to several companies for access to permits not held in their name, and to conduct scientific investigations in areas not currently held as tenements.

At the end of the year a number of applications were under consideration for areas gazetted as being available for issuing as exploration permits under the onshore petroleum act. Large areas in the sedimentary basins are currently available for application.

Petroleum tenements current on December 31st 1972 are shown on Figure 13, and the following tabulation lists details of the various holdings:

PETROLEUM TENEMENTS UNDER THE PETROLEUM (SUBMERGED LANDS) ACT 1967

Exploration Permits

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
WA-1-P	364	14/11/74	Woodside Oil N.L., Shell Development (Australia) Pty. Ltd., B.O.C. of Australia Ltd.
WA-2-P	381	14/11/74	West Australian Petroleum Pty. Ltd.
WA-7-P	135	10/7/75	Continental Oil Co. of Aust. Ltd.
WA-8-P	18	17/6/75	Coastal Petroleum N.L.
WA-9-P	56	17/6/75	" " "
WA-10-P	36	15/6/75	" " "
WA-12-P	5	11/9/75	Associated Australian Oilfields N.L.
WA-13-P	387	29/8/74	West Australian Petroleum Pty. Ltd.
WA-14-P	396	29/8/74	" " " " "
WA-15-P	352	20/3/75	Arco Aust. Ltd., Australian Aquitaine Petroleum Pty., Aust. Ltd., Esso Exploration & Production Aust. Inc.
WA-16-P	354	16/4/75	" " " " " "
WA-17-P	378	22/4/75	" " " " " "
WA-18-P	322	16/4/75	" " " " " "
WA-19-P	142	20/3/75	Alliance Oil Development Australia N.L.
WA-20-P	34	10/10/74	West Australian Petroleum Pty. Ltd.
WA-21-P	241	14/11/74	" " " " " "
WA-23-P	398	3/10/74	" " " " " "
WA-24-P	208	17/10/74	" " " " " "
WA-25-P	256	16/10/74	" " " " " "
WA-26-P	400	22/12/74	Canadian Superior Oil (Aust.) Pty. Ltd., Australian Superior Oil Co. Ltd., Philips Australian Oil Co., Sunray Australian Oil Co. Inc.
WA-27 P	294	18/5/75	" " " " " "
WA-28-P	375	24/3/75	Woodside Oil N.L., Shell Development (Australia) Pty. Ltd., B.O.C. of Australia Ltd.
WA-29-P	400	18/5/75	" " " " " "
WA-30-P	400	2/7/75	" " " " " "
WA-31-P	400	18/5/75	" " " " " "
WA-32-P	395	2/7/75	" " " " " "
WA-33-P	389	18/5/75	" " " " " "
WA-34-P	397	2/7/75	" " " " " "
WA-35-P	400	2/7/75	" " " " " "
WA-36-P	57	18/5/75	" " " " " "
WA-37-P	118	2/6/75	" " " " " "
WA-39-P	104	12/3/75	B.P. Petroleum Development Australia Pty. Ltd., Abrolhos Oil N.L.
WA-40-P	102	12/3/75	" " " " " "
WA-41-P	33	15/6/75	Coastal Petroleum N.L.
WA-43-P	241	17/9/78	Planet Exploration Company Pty. Ltd.
WA-44-P	400	17/9/78	" " " " " "
WA-47-P	195	5/6/78	Continental Oil Co. of Aust. Ltd.
WA-50-P	330	23/7/78	Esso Exploration & Production Aust. Inc.
WA-51-P	278	25/7/78	" " " " " "

PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT 1936

Petroleum Leases

Number	Area (square miles)	Expiry date of current term	Holders
IH	100	9/2/88	West Australian Petroleum Pty. Ltd.
2H	100	9/2/88	" " " " "

PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT 1967

Exploration Permits

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
EP 3	200	27/8/75	West Australian Petroleum Pty. Ltd.
EP 5	132	26/7/75	" " " " " "
EP 6	199	27/8/75	" " " " " "
EP 7	200	27/8/75	" " " " " "
EP 8	200	8/8/77	" " " " " "
EP 9	200	27/8/75	" " " " " "
EP 12	182	3/9/75	" " " " " "
EP 13	200	27/8/75	" " " " " "
EP 14	200	27/8/75	" " " " " "
EP 15	200	27/8/75	" " " " " "
EP 16	200	27/8/75	" " " " " "
EP 17	200	27/8/75	" " " " " "
EP 18	200	27/8/75	" " " " " "
EP 19	200	27/8/75	" " " " " "
EP 20	200	8/8/77	Australian Aquitaine Petroleum Pty. Ltd.
EP 21	90	26/7/75	West Australian Petroleum Pty. Ltd.
EP 23	163	6/8/75	" " " " " "
EP 24	167	6/8/75	" " " " " "
EP 25	96	6/8/75	" " " " " "
EP 26	1	27/8/75	BP Petroleum Development, Abrolhos Oil N.L.
EP 27	2	19/8/75	" " " " " "
EP 28	4	19/8/75	" " " " " "
EP 29	7	19/8/75	" " " " " "
EP 31	200	6/10/75	Beach-General Exploration Pty. Ltd., Australian Aquitaine Petroleum Pty. Ltd.
EP 32	200	15/4/76	" " " " " "
EP 33	123	15/4/76	" " " " " "
EP 34	1	15/4/76	Woodside Oil N.L., Shell Development (Australia) Pty. Ltd., B.O.C. of Australia Ltd.
EP 35	1	15/4/76	" " " " " "
EP 36	1	15/4/76	" " " " " "
EP 37	149	22/9/75	West Australian Petroleum Pty. Ltd.
EP 38	130	22/9/75	" " " " " "
EP 39	160	22/9/75	" " " " " "
EP 40	67	26/7/76	" " " " " "
EP 41	180	18/7/76	" " " " " "
EP 42	200	1/9/75	" " " " " "
EP 43	163	1/9/75	" " " " " "
EP 44	113	1/9/75	" " " " " "
EP 45	197	19/11/75	Continental Oil Co. of Aust. Ltd., Australian Sun Oil Co. Ltd.
EP 46	199	1/9/75	" " " " " "
EP 47	199	19/11/75	" " " " " "
EP 48	199	19/11/75	" " " " " "
EP 50	110	1/9/75	West Australian Petroleum Pty. Ltd.
EP 51	17	8/9/75	Lennard Oil N.L.
EP 52	18	8/9/75	" " "
EP 53	49	15/9/75	West Australian Petroleum Pty. Ltd.
EP 54	123	22/9/75	Alliance Oil Development Aust. N.L.
EP 55	178	22/9/75	West Australian Petroleum Pty. Ltd.
EP 58	200	20/7/76	Associated Australian Oilfields N.L., Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil N.L., Ashburton Oil N.L., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L.
EP 59	186	18/7/76	" " " " " "
EP 60	2	....	West Australian Petroleum Pty. Ltd.
EP 61	4	19/9/76	" " " " " "
EP 62	8	19/9/76	" " " " " "
EP 63	4	19/9/76	" " " " " "
EP 64	1	....	" " " " " "
EP 65	2	19/9/76	" " " " " "
EP 66	1	19/9/76	" " " " " "
EP 67	29	25/10/76	" " " " " "
EP 68	175	27/7/77	W. I. Robinson
EP 69	82	5/4/77	Sunningdale Oils Pty. Ltd.
EP 70	71	25/9/77	Associated Australian Oilfields N.L., Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil N.L., Ashburton Oil N.L., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L.
EP 71	81	6/7/77	Coastal Petroleum N.L.
EP 72	198	21/8/77	Planet Exploration Company Pty. Ltd.
EP 73	198	21/8/77	" " " " " "
EP 75	198	21/8/77	" " " " " "
EP 76	188	23/7/77	Genoa Oil N.L., Hartog Oil N.L., Olympus Petroleum N.L., Pexa Oil N.L., Omega Oil N.L., Kambalda Petroleum N.L.
EP 77	135	Appl'n	Stannon Engineering Co. Pty. Ltd.
EP 78	174	Appl'n	Planet Exploration Company Pty. Ltd.
EP 79	180	Appl'n	" " " " " "
EP 80	180	Appl'n	" " " " " "
EP 81	468	Appl'n	Officer Exploration Pty. Ltd.
EP 82	47	Appl'n	" " " "

Production Licences

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
PL 1	5	24/10/92	West Australian Petroleum Pty. Ltd.
PL 2	4	24/10/92	" " " " " "
PL 3	5	24/10/92	" " " " " "

PETROLEUM TENEMENTS UNDER THE PETROLEUM PIPELINES ACT, 1969

Pipeline Licences

Number	Expiry date of current term	Registered holder or applicant
1	1/12/91	California Asiatic Oil Co., Texaco Overseas Petroleum Co., Shell Development (Australia) Pty. Ltd., Ampol Exploration Ltd.
2	1/12/91	" " " " " " " " "
3	1/12/91	" " " " " " " " "
4	1/12/91	" " " " " " " " "
5	1/12/91	" " " " " " " " "

DRILLING

The positions of wells drilled for petroleum exploration in Western Australia during 1972 are shown on Figures 11 and 12. Details relating to the wells drilled during the year are given in Table 7. All of the petroleum exploration wells drilled in Western Australia up to the end of 1972 are listed in Geological Survey Record 1973/5.

A summary of the principal results of drilling in each basin during the year is as follows:

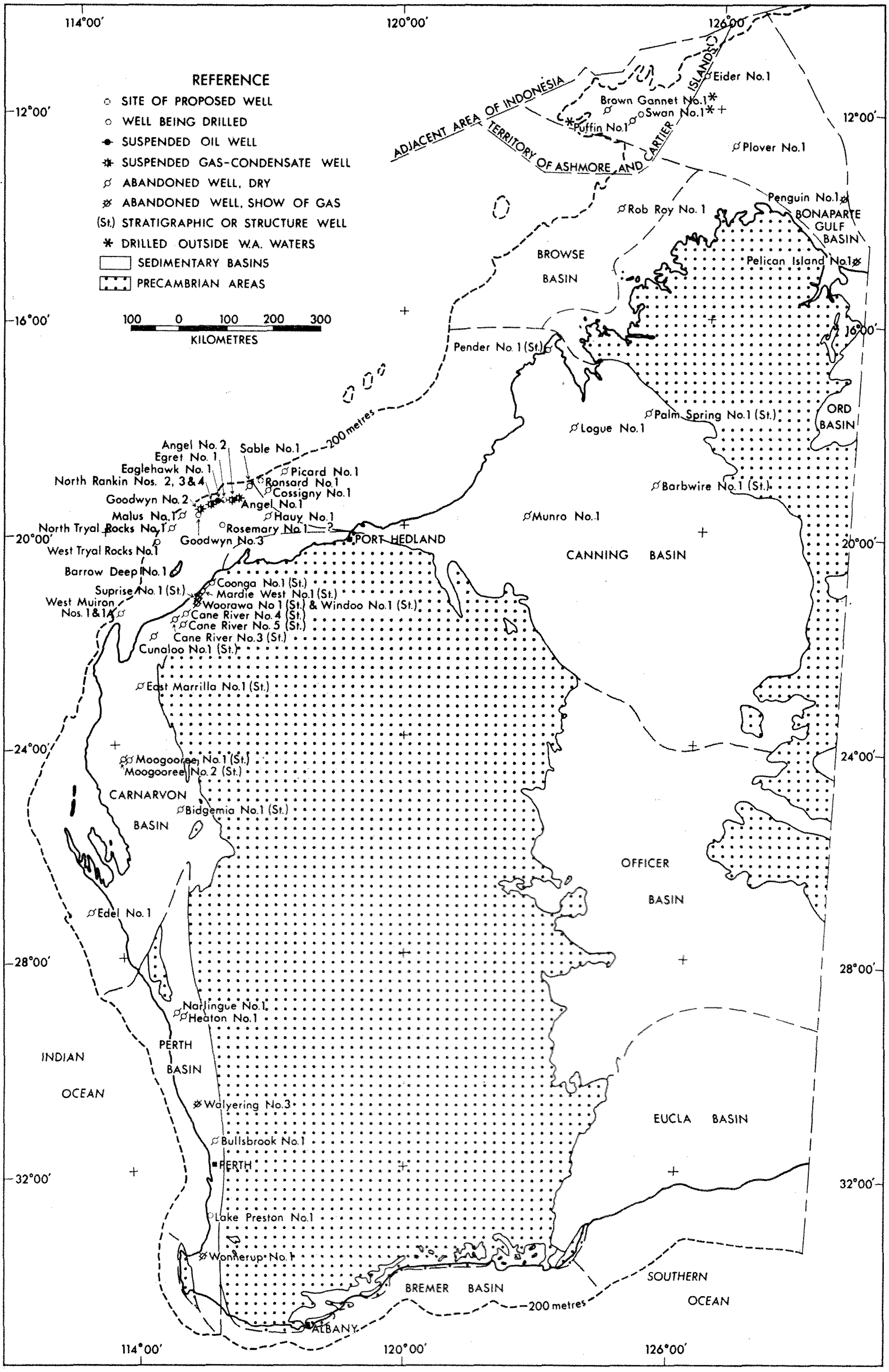

Figure 11. Wells drilled for petroleum exploration in W.A. during 1972.

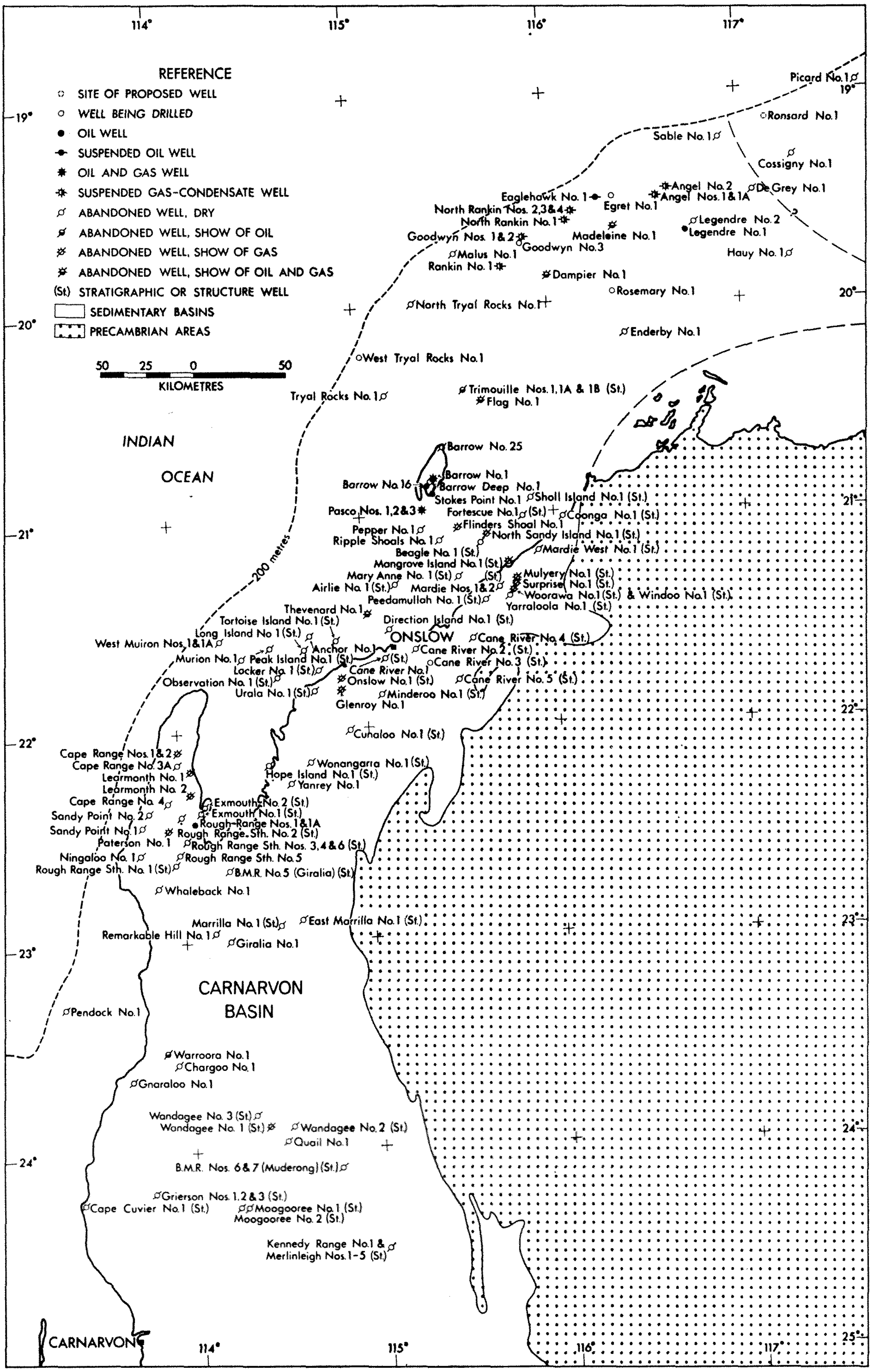

Figure 12. Wells drilled for petroleum exploration in the northern Carnarvon and southern Canning Basins to the end of 1972.

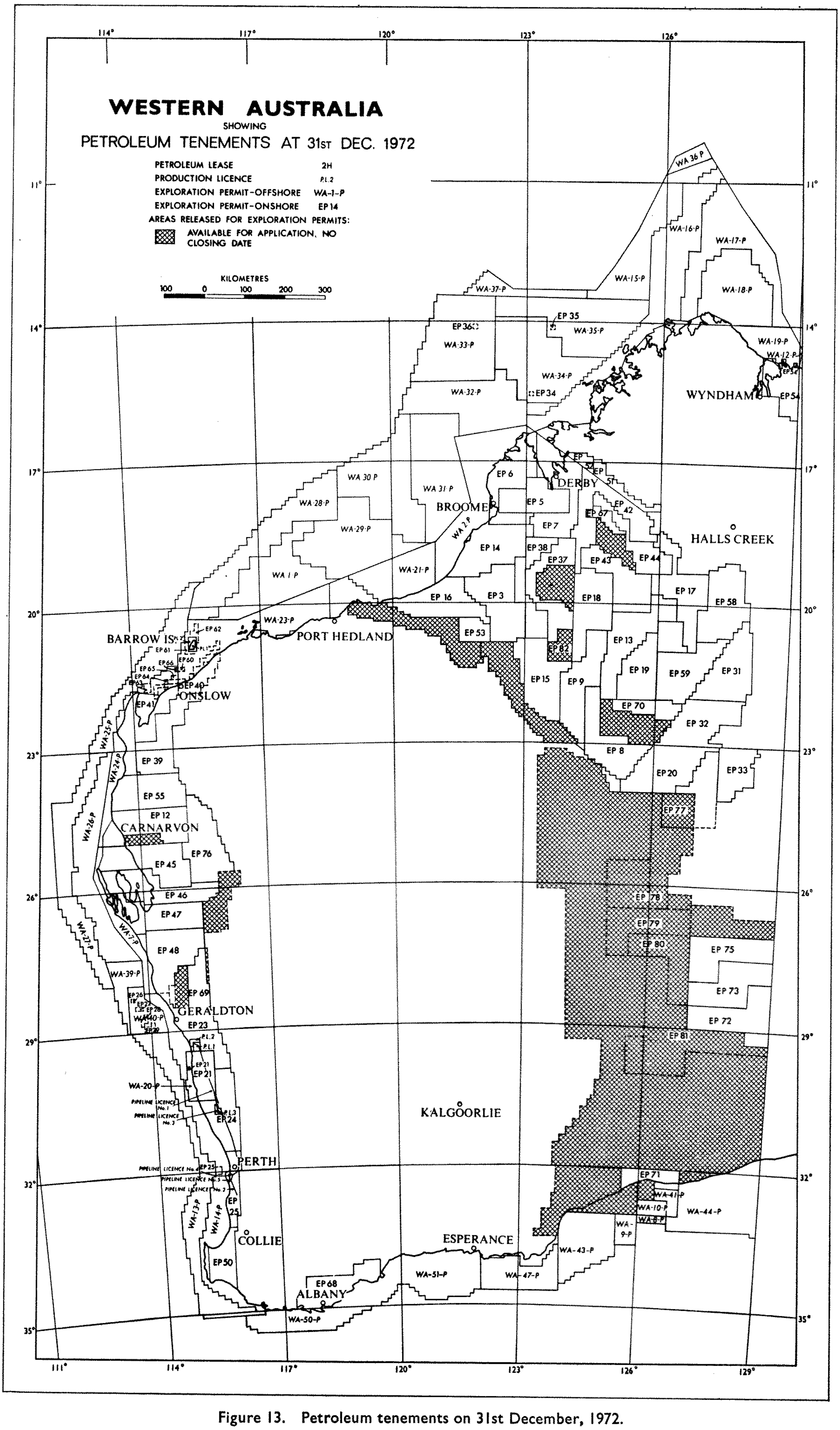

Figure 13. Petroleum tenements on 31st December, 1972.

TABLE 7. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1972

Basin	Well	*=Subsidized	Concession	Operating Company	Type	Position		Elevation and water depth (in metres)			Dates			Total depth (or depth reached) in metres	Bottomed in	Status 31 Dec. 1972
						Latitude South ° ′ ″	Longitude East ° ′ ″	G.L.	D.F.	W.D.	Commenced	Reached T.D.	Rig released			
Perth	Walyering No. 3		EP-24	WAPET	EXT	30 44 01	115 29 33	91·4	96·0	....	16/1/72	28/4/72	9/5/72	4,187	....	Gas shows P & A
	Narlingue No. 1	*	EP-23	ABROL	NFW	29 04 14	115 06 10	192·9	196·6	....	27/3/72	24/4/72	26/4/72	2,130	L. Permian	Dry, P & A
	Wonnerup No. 1	*	EP-50	UNION	NFW	33 37 55	115 28 16	15·9	24·1	....	18/4/72	3/8/72	9/8/72	4,727	U. Permian	Gas shows P & A
	Heaton No. 1	*	EP-23	ABROL	NFW	29 07 18	115 12 45	185·6	190·5	....	3/5/72	24/5/72	25/5/72	2,438	L. Permian	Dry, P & A
	Bullsbrook No. 1	*	EP-24	WAPET	NFW	31 28 41	115 50 28	86·3	90·8	....	1/10/72	27/11/72	30/11/72	4,257	L. Jurassic	Dry, P & A
	Lake Preston No. 1	*	EP-25	WAPET	NFW	32 55 13	115 39 32	10·1	14·6	....	20/12/72	....	....	1,384	....	Drilling
Carnarvon	Cane River No. 3		EP-40	HEMAT	STR	21 42 28	115 19 29	14·9	17·7	....	29/12/71	2/1/72	3/1/72	255	....	Dry, P & A
	Angel No. 1	*	WA-1-P	B.O.C.	NFW	19 30 20	116 35 48	....	9·4	79·8	12/10/71	11/1/72	22/1/72	3,671	U. Jurassic	G & C discovery Suspended
	Cane River No. 4		EP-40	HEMAT	STR	21 35 54	115 33 45	13·1	15·9	....	16/1/72	21/1/72	21/1/72	173	....	Dry, P & A
	Cane River No. 5		EP-40	HEMAT	STR	21 47 22	115 28 48	34·1	36·9	....	8/1/72	10/1/72	11/1/72	201	....	Dry, P & A
	Angel No. 2	* (part)	WA-1-P	B.O.C.	EXT	19 27 58	116 39 25	....	9·4	86·5	7/3/72	20/5/72	2/6/72	4,397	L. Jurassic	G & C well, Suspended
	Goodwyn No. 2		WA-28-P	B.O.C.	EXT	19 39 53	115 51 53	....	12·5	133·9	27/3/72	28/5/72	6/6/72	4,036	....	G & C well, Suspended
	Cunaloo No. 1	*	EP-39	WAPET	STR	22 00 48	114 53 47	12·3	15·2	....	22/3/72	31/3/72	1/4/72	797	U. Permian	Dry, P & A
	East Marrilla No. 1	*	EP-39	WAPET	STR	22 54 48	114 36 58	59·1	62·2	....	15/4/72	25/4/72	26/4/72	638	L. Carboniferous	Dry, P & A
	North Tryal Rocks No. 1	*	WA-25-P	WAPET	NFW	19 59 17	115 19 11	....	12·2	106·7	3/6/72	28/7/72	5/8/72	3,658	M. Triassic	Dry, P & A
	Edel No. 1	*	WA-26-P	OCEAN	NFW	27 06 46	113 23 22	....	29·5	94·5	24/5/72	20/7/72	25/5/72	2,749	Triassic	Dry, P & A
	North Rankin No. 2		WA-28-P	B.O.C.	EXT	19 33 54	116 08 48	....	12·5	126·2	9/6/72	1/8/72	20/8/72	3,750	....	G & C well Suspended
	Sable No. 1	*	WA-1-P	B.O.C.	NFW	19 14 04	116 54 59	....	22·5	140·8	21/8/72	12/10/72	14/10/72	3,647	?U. Triassic	Dry, P & A
	North Rankin No. 3		WA-28-P	B.O.C.	EXT	19 31 49	116 10 21	....	29·3	125·0	4/8/72	14/9/72	28/9/72	4,093	....	G & C well Suspended
	Barrow Deep No. 1	*	PL-1H	WAPET	DPT	20 50 07	115 22 57	38·7	46·6	....	16/9/72	....	....	3,238	....	Drilling
	West Muiron No. 1	*	WA-25-P	WAPET	NFW	21 33 56	114 14 41	....	12·2	142·0	16/8/72	18/9/72	4/10/72	781	U. Cretaceous	Dry, P & A
	West Muiron No. 1A	*	WA-25-P	WAPET	NFW	21 34 14	114 14 45	....	12·2	62·5	5/10/72	18/10/72	21/10/72	345	Tertiary	Dry, P & A
	North Rankin No. 4		WA-28-P	B.O.C.	EXT	19 35 07	116 06 42	....	30·2	127·1	30/9/72	11/11/72	23/11/72	4,062	....	G & C well Suspended
	West Tryal Rocks No. 1	*	WA-25-P	WAPET	NFW	20 13 45	115 02 04	....	12·2	137·8	23/10/72	....	....	3,091	....	Drilling
	Malus No. 1	*	WA-28-P	B.O.C.	NFW	19 45 16	115 32 03	....	9·7	85·6	7/10/72	6/11/72	....	3,658	U. Triassic	Dry, P & A
	Moogooree No. 1		EP-76	HARTOG	STR	24 15 20	115 15 30	253·0	253·6	....	8/10/72	15/10/72	15/10/72	128	....	Dry, P & A

Carnavon	Moogooree No. 2		EP–76	HARTOG	STR	24 16 50	115 12 40	257·5	258·1	....	18/10/72	27/10/72	4/11/72	192	....	Dry, P & A
	Woorawa No. 1		EP–40	HEMAT	STR	21 21 55	115 47 33	13·4	15·5	....	14/9/72	27/9/72	4/10/72	202	....	Gas show P & A
	Windoo No. 1		EP–40	HEMAT	STR	21 21 18	115 46 55	2·1	4·3	....	17/10/72	22/10/72	31/10/72	218	....	Gas show P & A
	Surprise No. 1		EP–40	HEMAT	STR	21 17 58	115 49 27	9·7	11·9	....	14/11/72	28/11/72	1/12/72	216	....	Gas show P & A
	Mardie West No. 1		EP–40	HEMAT	STR	21 11 56	115 55 24	6·4	8·5	....	5/12/72	8/12/72	11/12/72	135	....	Dry, P & A
	Coonga No. 1		EP–40	HEMAT	STR	21 03 08	116 01 48	5·8	7·9	....	14/12/72	19/12/72	20/12/72	176	....	Dry, P & A
	Bidgemia No. 1		EP–76	HARTOG	STR	25 16 00	115 20 20	201·7	202·2	....	6/11/72	23/11/72	23/11/72	228	....	Dry, P & A
	Eaglehawk No. 1	*	WA–1–P	B.O.C.	NFW	19 30 30	116 16 37	....	12·5	120·1	10/11/72	14/12/72	24/12/72	3,490	U. Triassic	Oil discovery Suspended
	Rosemary No. 1	*	WA–1–P	B.O.C.	NFW	19 57 16	116 20 41	....	9·5	64·9	13/11/72	....	....	2,845	....	Drilling
	Hauy No. 1	*	WA–1–P	B.O.C.	NFW	19 47 39	117 15 15	....	30·1	65·5	25/11/72	8/12/72	14/12/72	825	Precambrian	Dry, P & A
	Goodwyn No. 3		WA–28–P	B.O.C.	EXT	19 44 9	115 52 43	....	30·1	118·8	16/12/72	....	....	2,591	....	Drilling
	Egret No. 1		WA–28–P	B.O.C.	NFW	19 30 24	116 20 52	....	12·5	118·2	24/12/72	....	....	1,292	....	Drilling
Canning	Munro No. 1	*	EP–3	WAPET	NFW	19 51 55	122 29 19	51·2	55·8	....	4/6/72	30/6/72	3/7/72	2,116	Precambrian	Dry, P & A
	Pender No. 1	*	EP–6	WAPET	STR	16 40 48	122 50 06	21·0	24·1	....	15/5/72	21/5/72	22/5/72	912	L. Permian	Dry, P & A
	Barbwire No. 1	*	EP–43	WAPET	STR	19 10 38	125 00 59	215·5	218·5	....	18/6/72	6/7/72	6/7/72	774	M. Ordovician	Dry, P & A
	Palm Spring No. 1	*	EP–42	WAPET	STR	17 48 56	124 53 08	117·9	121·0	....	31/5/72	11/6/72	12/6/72	1,067	U. Devonian	Dry, P & A
	Picard No. 1	*	WA–1–P	B.O.C.	NFW	18 58 00	117 37 20	....	9·4	141·7	29/7/72	23/9/72	3/10/72	4,216	L. Jurassic	Dry, P & A
	Cossigny No. 1	*	WA–1–P	B.O.C.	NFW	19 19 53	117 17 26	....	12·8	111·5	15/10/72	5/11/72	8/11/72	3,203	?U. Triassic	Dry, P & A
	Logue No. 1	*	EP–7	WAPET	NFW	18 07 33	123 23 25	53·9	58·6	....	17/7/72	31/8/72	3/9/72	2,699	U. Devonian	Dry, P & A
Browse	Rob Roy No. 1	*	WA–35–P	B.O.C.	NFW	13 58 16	124 11 57	....	9·4	102·1	27/1/72	25/2/72	28/2/72	2,286	Precambrian	Dry, P & A
Bonaparte Gulf	Pelican Island No. 1....		EP–54	ARCO	NFW	14 46 19	128 46 27	7·9	12·2	....	29/5/72	27/7/72	29/7/72	1,981	....	Gas shows P & A
	Penguin No. 1		WA–17–P	ARCO	NFW	13 36 28	128 28 06	....	34·4	68·5	22/6/72	23/7/72	29/7/72	2,757	....	Gas shows P & A
	Eider No. 1		WA–15–P	ARCO	NFW	11 23 21	125 44 47	....	34·1	99·9	6/8/72	16/9/72	30/9/72	2,835	....	Dry, P & A
	Plover No. 1		WA–16–P	ARCO	NFW	12 42 45	126 22 07	....	34.0	57·9	10/11/72	14/12/72	17/12/72	2,438	....	Dry, P & A
												Total		106,185		
												Less drilling done in 1971		3,309		
												Total drilling done in 1972		102,876		

ABROL = Abrolhos Oil N.L.
ARCO = Arco Australia Ltd.
B.O.C. = B.O.C. of Australia Ltd.
HARTOG = Hartogen Explorations Pty. Ltd.
HEMAT = Hematite Petroleum Pty. Ltd.
OCEAN = Ocean Ventures Pty. Ltd.
UNION = Union Oil Development Corp.

WAPET = West Australian Petroleum Pty. Ltd.
DPT = Deeper Pool Test
EXT = Extension test well
NFW = New field wildcat well
P & A = Plugged and abandoned
STR = Stratigraphic well
G & C = Gas and condensate

PERTH BASIN

The results of drilling in the Perth Basin in 1972 were disappointing. Four test wells were drilled but, with the exception of Wonnerup No. 1 which yielded minor gas shows from Upper Permian sediments, all were dry. Some gas shows were encountered in the extension test well Walyering No. 3 but these were uneconomic and the well was plugged and abandoned.

The Lake Preston No. 1 new field wildcat well was drilling in the southern Perth Basin at the end of the year.

CARNARVON BASIN

Thirteen wells were spudded by the B.O.C. group in the Carnarvon Basin during 1972. Seven were new field wildcat wells and of these Angel No. 1 was a gas and condensate discovery, and Eaglehawk No. 1 was an oil discovery. The remaining six were extension tests. Five of these (Angel No. 2, Goodwyn No. 2, and North Rankin Nos. 2, 3 and 4) were successful gas and condensate wells and the other one, Goodwyn No. 3, was drilling at the end of the year.

Wapet spudded three new field wildcats. North Tryal Rocks No. 1 and West Muiron No. 1A were both dry and were plugged and abandoned, and West Tryal Rocks No. 1 was drilling at the end of the year. Electric logging has revealed indications of hydrocarbons in four zones totalling 46 m in this well. The deeper pool test Barrow Deep No. 1 was also drilling at the year's end, and promising indications of hydrocarbons have been encountered below 3,228 m.

Edel No. 1, a new field wildcat drilled offshore in the southern Carnarvon Basin by Ocean Ventures Pty. Ltd., was abandoned as a dry hole after reaching total depth in interbedded sandstones, siltstones and volcanics of probable Triassic age.

Two onshore stratigraphic wells, Cunaloo No. 1 and East Marrilla No. 1, were drilled by Wapet. Hematite Petroleum Pty. Ltd. drilled five shallow stratigraphic wells in EP-40 (under a farmout from Wapet), and Hartogen Exploration Pty. Ltd. drilled three shallow stratigraphic wells in EP-76.

The results obtained in the extension test wells in the Angel, Goodwyn and North Rankin fields are discussed in a separate report on petroleum development and production in 1972 (p. 40). Some details of the discovery wells are as follows:

Angel No. 1

Log evaluation and tests show that Upper Jurassic sands in the Barrow Group contain about 85 m gross hydrocarbon pay. This is wet gas with a condensate-to-gas ratio of about 1.8 barrels per thousand cubic metres of gas. The following is a summary of the results of the two drill stem tests run in the hole on a ⅝-inch bottom choke:

D.S.T. No.	Interval (metres)	Surface Choke	Gas x 10^3 m^3/d	Condensate b/d	Water b/d
1	2,734–2,737	⅝ inch	363·9	720	trace
2	2,685–2,688	⅝ inch	373·8	686	trace

Eaglehawk No. 1

Drill stem tests of Upper Triassic sands in Eaglehawk No. 1 yielded oil of 29.3 A.P.I. gravity, which is heavier than other oils recovered to date in Western Australia. A summary of the tests (through a ⅝-inch bottom choke) is as follows:—

D.S.T. No.	Interval (metres)	Surface Choke	Gas x 10^3 m^3/d	Oil b/d	Water b/d
1	2,777–2,788	....	nil	233	571
2	2,750–2,766	⅝ inch	3·99	1,645	nil

CANNING BASIN

During the year two offshore new field wildcat wells, two onshore new field wildcat wells, and three onshore stratigraphic wells were drilled in the Canning Basin. All were dry and were plugged and abandoned. The offshore wells, Picard No. 1 and Cossigny No. 1 were the first drilled in the Beagle Sub-basin in the southwestern Canning Basin.

BROWSE BASIN

Only one well, the new field wildcat Rob Roy No. 1, was drilled in the Browse Basin during 1972. The well penetrated Recent, Tertiary, Mesozoic, and Permian sediments before reaching total depth in Proterozoic quartzite. It was abandoned as a dry well.

BONAPARTE GULF BASIN

Four new field wildcat wells were drilled by Arco during the year in the part of the Bonaparte Gulf Basin under Western Australian control. All were abandoned as dry holes but there were some small gas shows in Pelican Island No. 1 and Penguin No. 1.

GEOPHYSICAL SURVEYS

SEISMIC

During 1972, seismic surveys were conducted in the Perth, Carnarvon, Canning, Browse, Bonaparte Gulf and Bremer Basins. Details are as follows:

SEISMIC SURVEYS

Basin	Permit No.	Company	Line Kilometres	
			Marine	Land
Perth	EP-21	West Australian Petroleum Pty. Ltd.	....	140
,,	EP-23	,, ,, ,,	....	45
,,	EP-24	,, ,, ,,	....	446
,,	EP-25	,, ,, ,,	....	188
,,	WA-13-P	,, ,, ,,	929	....
,,	WA-14-P	,, ,, ,,	559	....
,,	WA-20-P	,, ,, ,,	32	....
,,	WA-40-P	BP Petroleum Dev. Aust. Pty. Ltd.	224	....
Carnarvon	EP-12	West Australian Petroleum Pty. Ltd.	....	119
,,	EP-55	,, ,, ,,	....	103
,,	EP-47	Continental Oil Co. of Aust. Ltd.	....	72
,,	EP-48	,, ,, ,,	....	7
,,	WA-39-P	BP Petroleum Dev. Aust. Pty. Ltd.	814	....
,,	WA-23-P	West Australian Petroleum Pty. Ltd.	430	....
,,	WA-24-P	,, ,, ,,	558	....
,,	WA-75-P	,, ,, ,,	2579	....
,,	EP-41	,, ,, ,,	27	....
,,	WA-26-P	Canadian Superior Oil (Aust.) Pty. Ltd.	1187	....
,,	WA-7-P	Continental Oil Co. of Aust. Ltd.	415	....
Carnarvon/ Canning	WA-1-P	B.O.C. of Australia Ltd.	1199	....
	WA-28-P	,, ,, ,,	1877	....
Canning	EP-5	West Australian Petroleum Pty. Ltd.	....	129
,,	EP-6	,, ,, ,,	5	6
,,	EP-7	,, ,, ,,	....	117
,,	EP-13	,, ,, ,,	....	48
,,	EP-14	,, ,, ,,	....	108
,,	EP-17	,, ,, ,,	....	34
,,	EP-18	,, ,, ,,	....	119
,,	EP-19	,, ,, ,,	....	9
,,	EP-37	,, ,, ,,	....	101
	EP-38	,, ,, ,,	....	68
,,	EP-42	,, ,, ,,	....	219
,,	EP-43	,, ,, ,,	....	565
	EP-44	,, ,, ,,	....	352
,,	EP-67	,, ,, ,,	....	61
,,	EP-20	Australian Aquitaine Petroleum Pty. Ltd.	....	130
,,	EP-33	,, ,, ,,	....	80
,,	WA-2-P	West Australian Petroleum Pty. Ltd.	419	....
,,	WA-21-P	,, ,, ,,	1064	....
,,	WA-29-P	B.O.C. of Australia Ltd.	2461	....
,,	WA-31-P	,, ,, ,,	700	....
,,	WA-31-P	Amax Petroleum (Aust.) Inc.	990	....
,,	WA-30-P	Shell Development (Aust.) Pty. Ltd.	1803	....
,,	WA-30-P	Hematite Petroleum Pty. Ltd.	1442	....
Browse	WA-32-P	B.O.C. of Australia Ltd.	1149	....
,,	WA-33-P	,, ,, ,,	191	....
,,	WA-34-P	,, ,, ,,	1757	....
,,	WA-35-P	,, ,, ,,	666	....
,,	WA-37-P	,, ,, ,,	53	....
Bonarparte Gulf	WA-15-P	Arco Australia Ltd.	4025	....
	WA-16-P	,, ,, ,,	4826	....
,,	WA-17-P	,, ,, ,,	4776	....
,,	WA-18-P	,, ,, ,,	4169	....
,,	WA-19-P	,, ,, ,,	436	....
,,	EP-54	,, ,, ,,	495	....
,,	WA-12-P	Australian Aquitaine Petroleum Pty. Ltd.	3	....
Bremer	WA-47-P	Continental Oil Co. of Aust. Ltd.	958	....
		Totals	43,218	3,266

GRAVITY

Gravity surveys were carried out during the year in the Perth, Carnarvon, and Canning Basins, and the majority of these were shipboard. Details are as follows:

GRAVITY SURVEYS

Basin	Permit No.	Company	Party Months	Ship-board Line, Kilometres
Perth	WA-40-P	BP Petroleum Development Aust. Pty. Ltd.	0·25	....
,,	WA-13-P	West Australian Petroleum Pty. Ltd.	....	504
,,	WA-14-P	,, ,, ,,	....	35
,,	WA-20-P	,, ,, ,,	....	32
Carnarvon	EP-45	Continental Oil Co. of Aust. Ltd.	2·2	....
,,	EP-46	,, ,, ,,	2·5	....
,,	EP-47	,, ,, ,,	3·5	....
,,	EP-48	,, ,, ,,	2·0	....
,,	EP-41	West Australian Petroleum Pty. Ltd.	....	21
,,	WA-23-P	,, ,, ,,	....	333
,,	WA-24-P	,, ,, ,,	....	319
,,	WA-25-P	,, ,, ,,	....	2049
Canning	WA-2-P	West Australian Petroleum Pty. Ltd.	....	454
,,	WA-21-P	,, ,, ,,	....	615
		Totals	10·45	4,362

MAGNETOMETER

Aeromagnetic surveys were conducted in the Canning and Bremer Basins, and ship-board magnetometer in the Perth, Carnarvon and Canning Basins. Details are as follows:

MAGNETOMETER SURVEYS

Basin	Permit No.	Company	Line Kilometres	
			Aero-magnetic	Ship-board
Perth	WA-13-P	West Australian Petroleum Pty. Ltd.	....	504
,,	WA-14-P	,, ,, ,,	....	35
,,	WA-20-P	,, ,, ,,	....	32
,,	WA-40-P	BP Petroleum Development Aust. Pty. Ltd.	....	107
Carnarvon	EP-41	West Australian Petroleum Pty. Ltd.	....	21
,,	WA-23-P	,, ,, ,,	....	333
,,	WA-24-P	,, ,, ,,	....	319
,,	WA-25-P	,, ,, ,,	....	2049
Canning	EP-5	West Australian Petroleum Pty. Ltd.	1228	....
,,	EP-7	,, ,, ,,	2558	....
,,	EP-17	,, ,, ,,	931	....
,,	EP-42	,, ,, ,,	7211	....
,,	EP-44	,, ,, ,,	3416	....
,,	EP-67	,, ,, ,,	1604	....
,,	WA-2-P	,, ,, ,,	....	454
,,	WA-21-P	,, ,, ,,	....	615
,,	EP-51-52	Lennard Oil N.L.	2897	....
,,	WA-30-P	Hematite Petroleum Pty. Ltd.	....	550
Bremer	WA-50-P	Esso Exploration and Production Aust. Inc.	3800	....
,,	WA-51-P	,, ,, ,,	2800	....
		Totals	26,445	5,019

GEOLOGICAL SURVEYS

Field geological investigations were carried out by oil exploration tenement holders in the Canning and Bremer Basins. Details are as follows:

Basin	Permit No.	Company	Geologist months
Carnarvon	EP-76	Hartogen Explorations Pty. Ltd.	3
Canning	EP-17	West Australian Petroleum Pty. Ltd.	2
,,	EP-42	,, ,, ,, ,,	2
,,	EP-58	Associated Australian Oilfields N.L.	2
,,	EP-59	,, ,, ,, ,,	2
Bremer	WA-50-P	Esso Exploration and Production Aust. Inc.	1
,,	WA-51-P	,, ,, ,, ,,	1
		Total	13

GEOCHEMICAL SURVEYS

A geochemical survey was conducted over a part of the Lennard Shelf in the Canning Basin. Details are as follows:

Basin	Permit No.	Company	Field work
Canning	EP-51-52	Lennard Oil N.L.	265 samples taken over 106·5 line kilometres

PETROLEUM DEVELOPMENT AND PRODUCTION IN WESTERN AUSTRALIA IN 1972

by R. N. Cope

ABSTRACT

From the Barrow Island Oilfield a total production of 15,458,891 barrels of oil was achieved in 1972 by means of a waterflood secondary recovery scheme. Of the 199.350 x 10^6 m^3 of gas produced, 9.7 per cent was used as field fuel. Installation of three compressors along the Dongara-Perth-Pinjarra gas pipeline allowed production from the Dongara and Mondarra Fields to be raised to a previously unattained level, the combined December daily average being 2.1832 x 10^6 m^3. Production from Walyering No. 1 totalled 7.377 x 10^6 m^3 over a period of 4 months before declining pressure enforced shut-in, and experimental production over 10 months from Gingin No. 1 totalled 40.404 x 10^6 m^3.

In the northern Carnarvon Basin part of the Northwest Shelf proven and probable gas reserves have been estimated by B.O.C. as 566 x 10^9 m^3 following drilling of appraisal wells in the North Rankin, Goodwyn and Angel Fields. Gas reserves of the North Rankin Field are put at 285 x 10^9 m^3 by B.O.C.

INTRODUCTION

Western Australia has two petroleum fields in the course of long-term planned production, the Barrow Island Oilfield, and the Dongara Gasfield, both operated by West Australian Petroleum Pty. Ltd. (referred to here as Wapet). At Barrow Island production has again declined slightly. However, the Dongara Gasfield achieved peak production during the year. In addition, Walyering No. 1 produced gas into the Dongara-Perth-Pinjarra pipeline for 4 months. Gas produced from the prolonged production testing of Gingin No. 1 for nearly 10 months was also fed into the pipeline.

Total throughput for the Dongara-Perth-Pinjarra pipeline was 664.504 x 10^6 m^3. During December the average daily throughput was 2.294 x 10^6 m^3, a figure made possible by the installation of three compressors. No. 3 compressor (173.2 km from the Dongara separation and dehydration plant) was commissioned on 20th July, No. 2 (at 116.4 km) on 20th August and No. 1 (at 58.1 km) on 25th December.

Appraisal of gas pools discovered in 1971 by Burmah Oil Company of Australia Pt. Ltd. (refered to in this report as B.O.C.) took place in the northern Carnarvon Basin portion of the Northwest Shelf. Development may be confidently anticipated once substantial reserves have been proven but, owing to the large scale of an economic exploitation project and the special geographical problems involved, production seems unlikely to eventuate for some years.

Production and test flows of gas are expressed in cubic metres while liquids are expressed in barrels, both at standard conditions of 60 degrees Fahrenheit and 14.73 psia.

BARROW ISLAND OILFIELD

Since the start of production in 1967 cumulative production from the Barrow Island Oilfield has amounted to 77,463,136 barrels, of which 15,458,891 barrels were produced in 1972 (Table 8).

TABLE 8. BARROW ISLAND PRODUCTION 1972

Reservoir	Average Daily Prod. Oil (bbls) during December 1972	Production for year 1972			Cumulative Production		
		Oil (bbls)	Water (bbls)	Gas x $10^6 m^3$	Oil (bbls)	Water (bbls)	Gas x $10^6 m^3$
Windalia	40,652	15,185,988	5,566,788	175·911	75,267,395	11,321,642	1,334·140
Muderong	378	154,323	46,653	3·411	845,512	161,926	20·028
Jurassic 5,500′	....	....	....	....	15,580	101,628	14·620
Jurassic 6,200′	....	3,363	13,523	9·111	57.489	123,952	80·893
Jurassic 6,600′	58	21,094	80,423	1·201	230,389	355,763	18·072
Jurassic 6,700′	195	94,123	64,135	9·716	1,046,771	268,508	83·862
Total field	41,283	15,458,891	5,771,522	199·350	77,463,136	12,333,419	1,551·615

Water injected 1972: 41,144,564 bbls

Cumulative water injected : 139,617,839 bbls

Peak production was achieved in September, 1970 with an average of 49,803 barrels per day. During 1972 there was a further decline from an average of 43,617 barrels per day in December, 1971 to 41,283 barrels per day in December, 1972. The main reservoir is the Lower Cretaceous "Windalia Sand" which accounted for 98 per cent of production during 1972. Owing to the very low permeability of this reservoir, achievement of a reasonable recovery factor depends on a waterflood secondary-recovery scheme (Table 9 and Fig. 14).

TABLE 9. BARROW ISLAND WELL STATUS BY RESERVOIRS AT 31ST DECEMBER, 1972

Reservoir	Flowing	Pumping	Gas Lift	Closed in	Water injection	Water Source	Water disposal	Total
Windalia	23	175	110	11	157	9	7	492
Muderong	2	3	3	....	....	....	....	8
Jurassic 5,500′	....	....	....	1	....	....	....	1
Jurassic 6,200′	....	....	....	2	....	....	....	2
Jurassic 6,600′	1	....	....	....	....	....	....	1
Jurassic 6,700′	1	1	1	2	....	....	....	5
Total	27	179	114	16	157	9	7	509

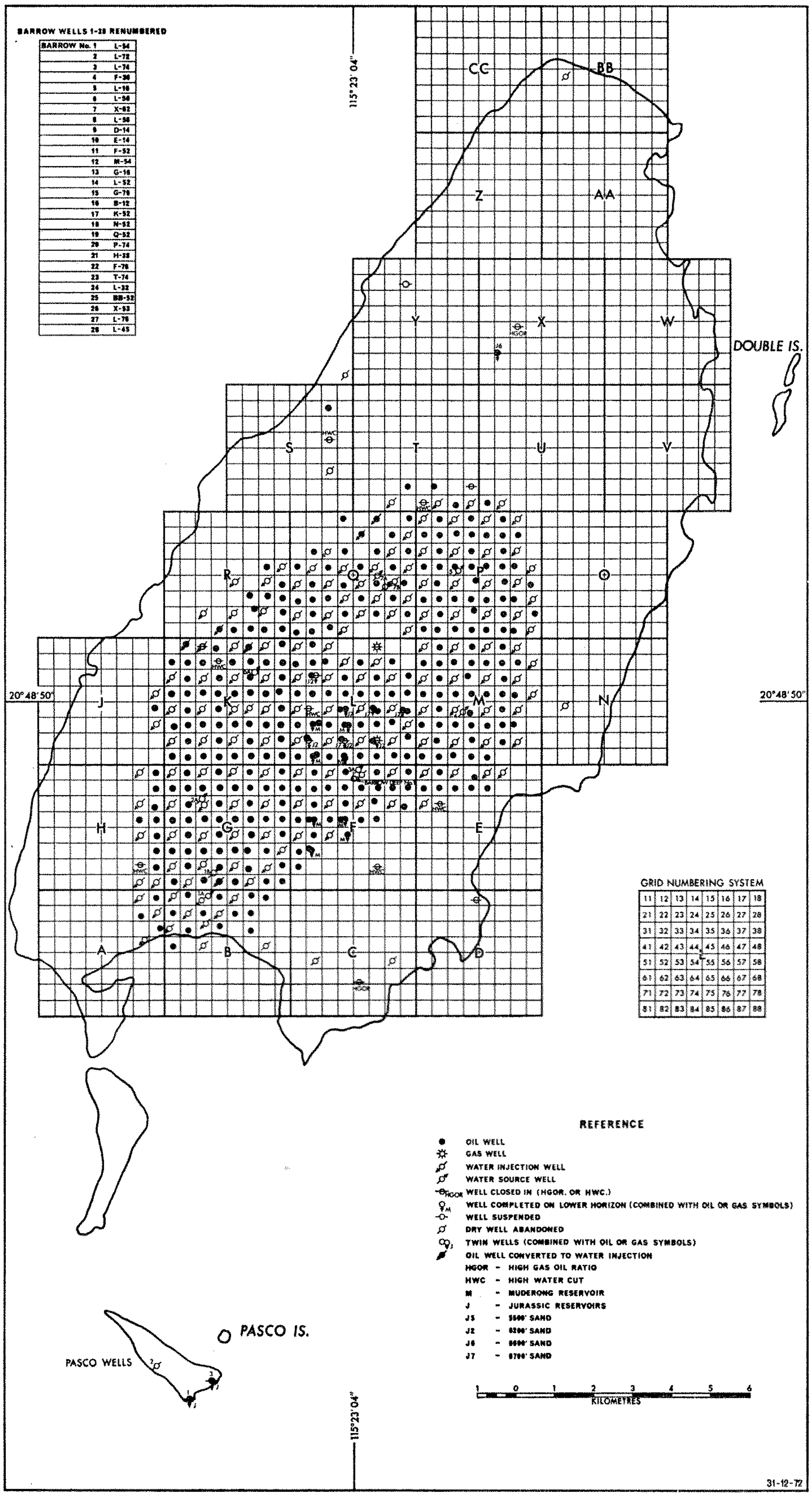

Figure 14. Barrow Island area. Windalia Reserve.

This scheme has so far operated quite successfully but it is nevertheless difficult to establish firmly the final recovery factor and therefore the ultimate reserves. A nominal initial reserves figure of 200 million barrels of oil was released at an early stage. Remaining nominal reserves at the end of 1972 were 133 million barrels. The production history of the Barrow Island Oilfield up to late 1972 has now been published (Crank, 1973).

A total of 199.350 x 10^6 m^3 of gas was produced during 1972, of which 9.7 per cent was used as field fuel and the remainder flared (Table 10). A low-temperature separation plant to recover natural gasoline and liquid petroleum gas from the natural gas prior to flaring was installed, but was operating only on an experimental basis at the end of 1972.

TABLE 10. BARROW ISLAND OIL AND GAS DISPOSAL 1972

	Oil (bbls)	Gas (m^3 x 10^6)
Total production	15,458,891	199·350
Field fuel	....	17·110
Gas flared	....	182·240
Oil shipments	15,427,836	....
Percentage of field utilization	....	9·7
Percentage of gas flared	....	90·3
Royalty received	A$1,452,402	....

NOTE : 1 m^3 = 35·315 cu ft

TABLE 11. PETROLEUM PRODUCTION FROM PERTH BASIN FIELDS 1972

Field	Number of producing wells at 31/12/72	Gas (m^3 x 10^6)		Condensate (bbls)		Water (bbls)	
		Total	Average daily during December	Total	Average daily during December	Total	Average daily during December
Dongara	10	571·531	1·9745	22,881	63·3	15,686	50
Mondarra	1	43·322	0·2087	6,024	29	1,508	7
Yardarino	....	....	....	....	....	....	....
Walyering	....	7·377	....	1,493	....	1,429	....
Gingin	....	40·404	0·1051	16,912	32	10,745	30
Totals	11	662·634	2·2883	47,310	124·3	29,368	87

Total gas sold :	664·504 m^3 x 10^6
Total royalties received	A$152,472.8

On 16th September 1972, Barrow Deep No. 1 was spudded with the objective of testing the prospects of the structure between the maximum previous depth attained (2,983 m in Barrow No. 1) and 4,877 m. In December, 1972 high pressure gas was encountered at a depth of 3,239 m.

DONGARA FIELD

Details of gas and condensate production from the Dongara field are given in Table 11. Production from Dongara increased substantially during the year from an average daily production in December, 1971 of 729 x 10^3 m^3 to 1.975 x 10^6 m^3 in December, 1972 (Fig. 15). Three compressors were installed along the Dongara-Perth-Pinjarra pipeline to allow the increased throughput. The condensate was disposed of by road tanker to Kwinana. For the position of the Dongara Field and other Perth Basin fields refer to Cope, 1972, Figure 16.

MONDARRA FIELD

Production from the relatively small Mondarra Field, some 15 km southeast of the Dongara Field, started on 17th April, 1972. During December the average daily production was 0.2087 x 10^6 m^3 of gas (Fig. 15).

WALYERING FIELD

The discovery well, Walyering No. 1 and an extension test well, Walyering No. 2 were drilled in 1971. Production License No. 3 covering the Walyering Field was issued also in that year. A further

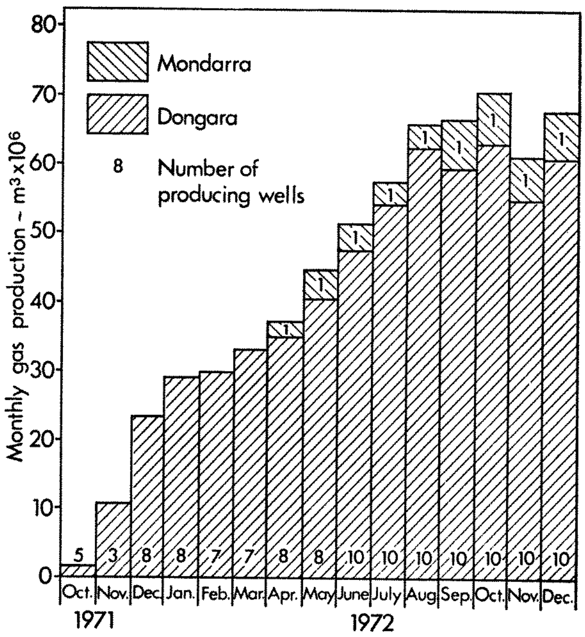

Figure 15. Monthly gas production from Dongara and Mondarra Fields 25th October, 1971 to 31st December, 1972.

extension test well (Fig. 16) was spudded, about 1.8 km southeast of Walyering No. 1, on 16th January, 1972 and reached a total depth of 4,187 m on 28th April, 1972.

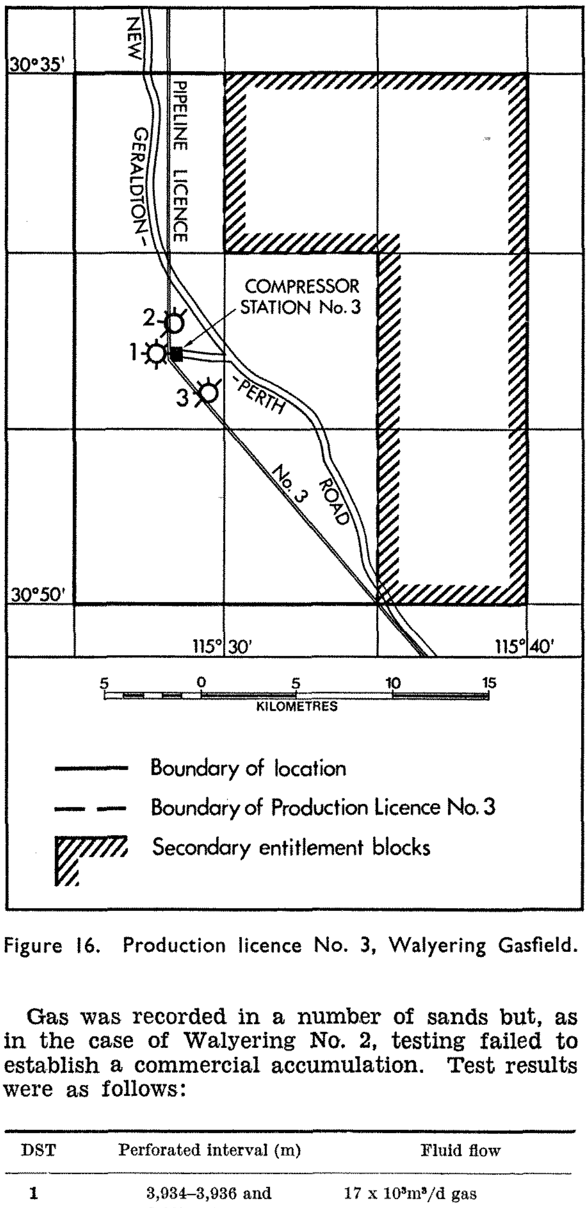

Figure 16. Production licence No. 3, Walyering Gasfield.

Gas was recorded in a number of sands but, as in the case of Walyering No. 2, testing failed to establish a commercial accumulation. Test results were as follows:

DST	Perforated interval (m)	Fluid flow
1	3,934–3,936 and 3,937–3,939	17 x $10^3 m^3$/d gas
2	3,908–3,912	5·7 x $10^3 m^3$/d gas
3	3,695–3,701	60 b/d water plus an amount of gas too small to measure

Under Production License 3, production of gas from Walyering No. 1 started on 23rd March. Maximum average daily production (97.047 m^3) was reached in June but pressure decline led to the shutting-in of the well on 23rd July (Fig. 17). The total production from Walyering No. 1 into the Dongara-Perth-Pinjarra pipeline was 7.377 x 10^6 m^3 (Table 11).

GINGIN FIELD

Prolonged production testing of Gingin No. 1 was conducted between 6th March and 31st December, 1972 under temporary special arrangements with the State Government. The monthly production was variable as shown in Figure 17. The total production into the pipeline was 40,404 x 10^6 m^3 (Table 11).

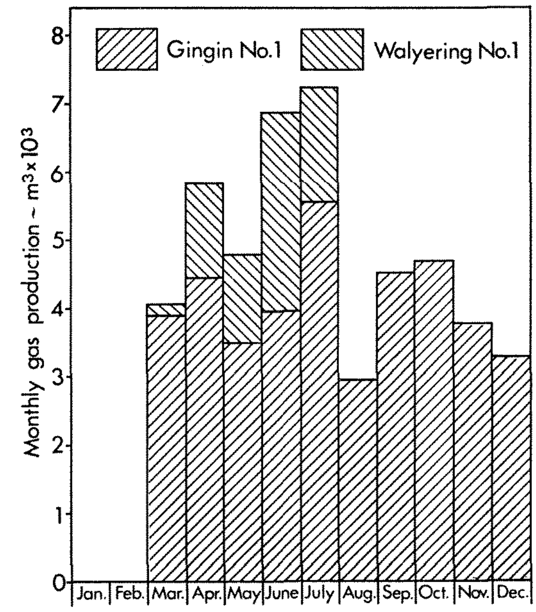

Figure 17. Monthly gas production from Walyering No. 1 and Gingin No. 1 during 1972.

NORTHWEST SHELF

GENERAL

Of the five gas discoveries made in 1971 by B.O.C. three were the subject of some degree of appraisal drilling (Fig. 18). Three wells were drilled on the North Rankin Field, one on Goodwyn and one on Angel. A further appraisal well was drilling on the Goodwyn Field at the end of the year. The discovery of heavy oil (27.6° A.P.I.) in Eaglehawk No. 1 further enhanced the prospect of the area.

In December, 1972 Woodside-Burmah Oil N. L. announced that "for the fields in the Rankin area, excluding Scott Reef, the total recoverable reserve figure in the proved, probable and possible categories of 20 trillion cubic feet could be established". This figure is equivalent to 566 x 10^9 m^3 and was put forward merely as an estimate based on rule of thumb methods.

Published information on the Northwest Shelf has recently been extended from the exploration to the appraisal stage (Martison and others, 1972). The main gas-bearing formation on the Rankin Shelf is the Upper Triassic Mungaroo Formation, while in North Rankin No. 1 a small flow of gas and a small amount of oil were recovered from the Upper Cretaceous Toolonga Calcilutite (Kaye and others, 1972). It has now been demonstrated that the crudes of the northern Carnarvon Basin may be differentiated. The Jurassic crudes (Legendre No. 1 and Barrow Jurassic) are primarily naphthenic to aromatic whilst the Barrow Cretaceous (Windalia) oil is distinctly aromatic (Powell and McKirdy, 1972).

NORTH RANKIN FIELD

The North Rankin Field covers an area of about 67 km^2 and lies about 120 km from the mainland. Following up the very encouraging discovery well, in which 311 m of net pay was encountered in a gross gas-bearing interval of 564 m, North Rankin No. 2 was spudded on 9th June, 1972 about 4.5 km northeast of North Rankin No. 1. It reached a total depth of 3,750 m on 1st August, 1972. Results of the four drill stem tests were as follows:

DST	Perforated Interval (m)	Choke sizes (inches) Bottom	Choke sizes (inches) Surface	Gas flow x $10^3 m^3$/d	Condensate recovered b/d
1a	3,168–3,197	$\frac{3}{4}$	$\frac{5}{8}$	518	517
1b	3,168–3,197	$\frac{3}{4}$	$\frac{7}{8}$	603	....
2	2,842–2,868	$\frac{3}{4}$	$\frac{7}{8}$	578	512
3	2,758–2,763	$\frac{3}{4}$	$\frac{5}{8}$	309	278
4	2,719–2,736	$\frac{3}{4}$	$\frac{7}{8}$	530	484

Together with formation interval tests, these confirmed a net hydrocarbon pay of porous and permeable sands of 383 m within a gross reservoir section of 503 m.

North Rankin No. 3 was spudded 5 km northeast of No. 2 on 4th August, 1972 and reached a total depth of 4,093 m on 14th September, 1972. Drill stem test no. 1 of the interval 3,092-3,138 m flowed 793 x 10^3 m^3/d of gas and 796 b/d condensate on a $\frac{3}{4}$-inch surface choke. This was followed directly by North Rankin No. 4, 2 km northwest of North Rankin No. 1, which was spudded on 30th September and reached a total depth of 4,062 m on 11th November, 1972. Testing of the interval 2,977-2,998 m resulted in a flow of 2.12 x 10^3 m^3/d gas and 202 b/d condensate on a $\frac{3}{4}$-inch choke.

In the December, 1972 reserve statement by B.O.C. the proved and probable recoverable gas in the North Rankin Field, assuming a recovery factor of 55 per cent, is put at 10.17 trillion cubic feet or 285 x 10^9 m^3.

GOODWYN FIELD

Goodwyn No. 2 was spudded, in a position 4.6 km northwest of Goodwyn No. 1, on 27th March and reached a total depth of 3,750 m on 28th May, 1972. An Upper Triassic pay zone was encountered between 2,835 m and 2,892 m with 21 m of net pay. The gas/water contact is thus some 270 m higher in Goodwyn No. 2 than in Goodwyn No. 1. No drill stem tests were conducted, but formation interval tests established the condensate ratio to range between 2.54 and 3.75 barrels per thousand cubic metres, these being the highest values so far encountered in this area.

These results indicate that the Goodwyn Field is complex and that it requires much more appraisal before reserves can be confidently estimated. Goodwyn No. 3 was spudded on 16th December, 1972 in a position 5 km south-southwest of Goodwyn No. 1, and at the end of the year had reached a depth of 2,590 m.

ANGEL FIELD

The Angel No. 1 gas discovery early in 1972 was followed up by Angel No. 2 about 8 km to the northeast. This extension test well was spudded on 7th March and reached a total depth of 4,397 m on 21st May, 1972. The portion between 2,758 m and total depth is classified as an exploration hole and was subsidised under the Petroleum Search Subsidy Act. Results of drill stem testing were as follows:

DST	Perforated Interval (m) BDF	Choke sizes (inches) Bottom	Choke sizes (inches) Surface	Gas Flow x $10^3 m^3$/d	Condensate recovered b/d
1	2,742–2,750	$\frac{5}{8}$	$\frac{5}{8}$	316	586
2	2,718–2,722	$\frac{5}{8}$	$\frac{1}{2}$	209	377
3	2,697–2,705	$\frac{5}{8}$	$\frac{5}{8}$	342	632

Further appraisal is necessary before reserves can be confidently estimated.

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TESTS OF A PROTOTYPE 3MHz ELECTROMAGNETIC METHOD

by N. Watanabe* and J. L. Baxter

ABSTRACT

Testing of a prototype electromagnetic method using a complex transmission frequency of 3MHz indicates that the method may be suitable for mineral exploration in Western Australia. Significant responses were obtained in traverses over hematite, oxide ores of copper, and nickel sulphides. Massive nickel suphides were detected under a highly conductive surface layer. The equipment is capable of detecting responsive minerals to depths of 300 to 500 m. The adjustment of the prototype equipment necessary to obtain the best operating conditions proved difficult in the field. Surveying was carried out on a regional traverse at speeds of up to 65 km per hour, and satisfactory results were obtained.

INTRODUCTION

In 1971, Professor H. Kikuchi, of the Department of Electrical Engineering, College of Engineering, Nihon University, asked the Western Australian Government to co-operate in testing a new electromagnetic prospecting method. His request was approved by the West Australian Minister for Mines and a post-graduate student from Nihon University, N. Watanabe, came to Western Australia to test the equipment in September, 1972.

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Twelve different sites were selected to test the method on a variety of ore minerals in areas of different climate, geology and hydrology. The results of testing of six of these areas have been selected for presentation in this report, which is condensed from a full report by Watanabe and Baxter (1972).

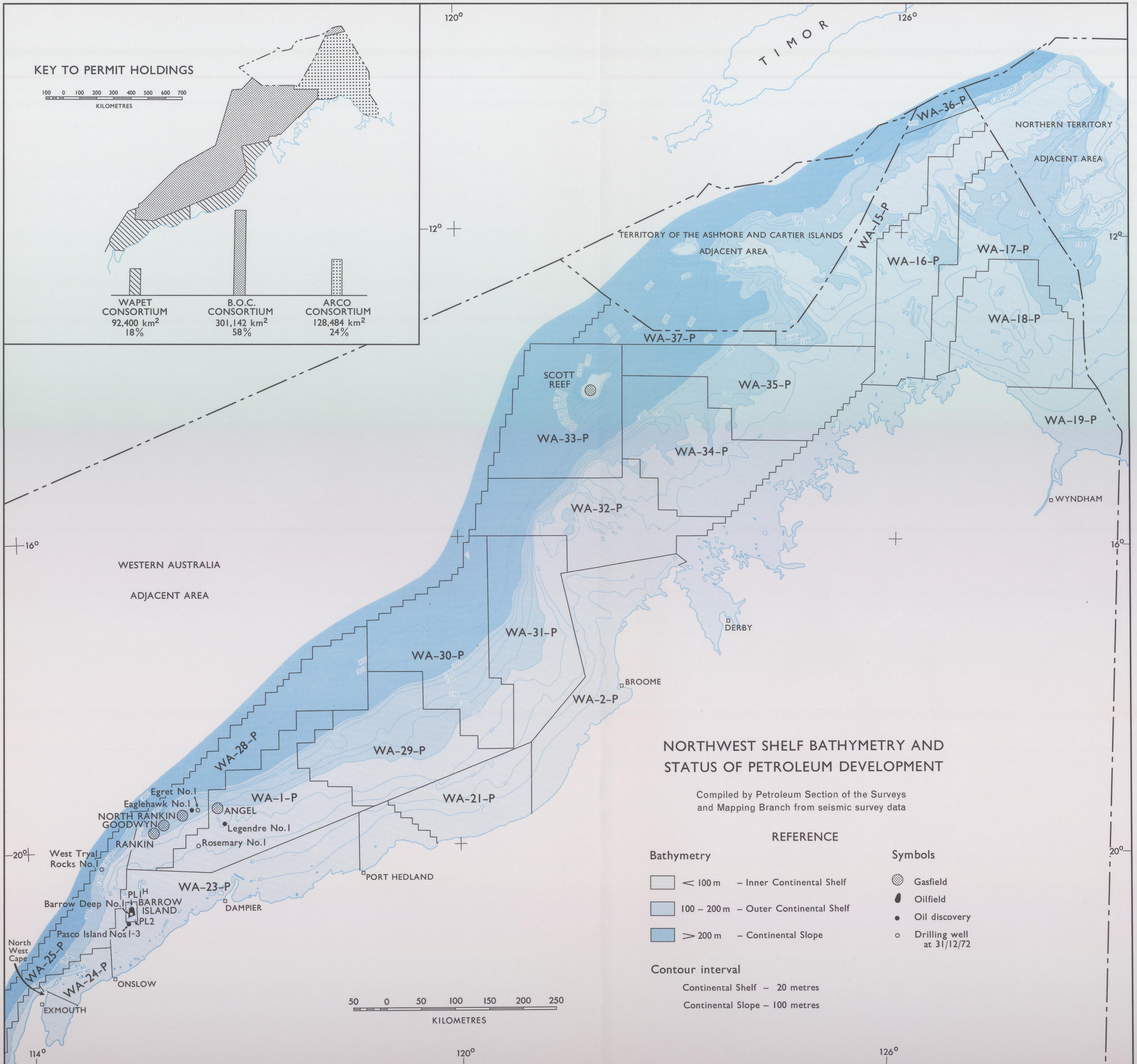
All of the areas investigated were held by exploration companies and, as there is a need to maintain security on some of the information presented, no localities are given.

ACKNOWLEDGEMENTS

Thanks are expressed to Mr. Fred Tanaka, Mr. Shinobu Takahashi, Misses Jo-anne Green and Sue Moulton, Mr. Neville Saunders, and Dr. Duncan Steven of the Western Australian Institute of Technology, the University of Western Australia, and the Nomura Trading Company for help in translation and interpretation. Sincere thanks are also due to the companies who provided information and target sites during the testing.

SUMMARY OF THE OPERATION OF THE EQUIPMENT

The equipment consists essentially of three oscillators (O_0, O_1 and O_2), two demodulators, and a phase meter as shown in the block diagram (Fig. 19). The standard oscillator (O_0) produces a



KEY TO PERMIT HOLDINGS
100 0 100 200 300 400 500 600 700
KILOMETRES
WAPET CONSORTIUM 92,400 km2 18%
B.O.C. CONSORTIUM 301,142 km2 58%
ARCO CONSORTIUM 128,484 km2 24%
TIMOR
TERRITORY OF THE ASHMORE AND CARTIER ISLANDS
ADJACENT AREA
NORTHERN TERRITORY
ADJACENT AREA
WESTERN AUSTRALIA
ADJACENT AREA
WA-36-P
WA-15-P
WA-16-P
WA-17-P
WA-18-P
WA-19-P
WA-37-P
WA-35-P
WA-34-P
WA-33-P
WA-32-P
WA-31-P
WA-30-P
WA-2-P
WA-29-P
WA-28-P
WA-1-P
WA-21-P
WA-23-P
WA-24-P
WA-25-P
SCOTT REEF
WYNDHAM
DERBY
BROOME
PORT HEDLAND
DAMPIER
ONSLOW
EXMOUTH
North West Cape
Egret No.1
Eaglehawk No.1
NORTH RANKIN
GOODWYN
ANGEL
Legendre No.1
Rosemary No.1
RANKIN
West Tryal Rocks No.1
Barrow Deep No.1
PL1
BARROW ISLAND
PL2
Pasco Island Nos 1-3
NORTHWEST SHELF BATHYMETRY AND STATUS OF PETROLEUM DEVELOPMENT
Compiled by Petroleum Section of the Surveys and Mapping Branch from seismic survey data
REFERENCE
Bathymetry
< 100 m – Inner Continental Shelf
100 – 200 m – Outer Continental Shelf
> 200 m – Continental Slope
Symbols
Gasfield
Oilfield
Oil discovery
Drilling well at 31/12/72
Contour interval
Continental Shelf – 20 metres
Continental Slope – 100 metres
50 0 50 100 150 200 250
KILOMETRES
114°
120°
126°
12°
16°
20°

Figure 18

signal of 3MHz. The frequency difference between the two oscillators O_1 and O_2 and the standard oscillator is approximately 1KHz. It is possible to adjust the two oscillators (O_1 and O_2) to add or subtract an increment of frequency (δ f).

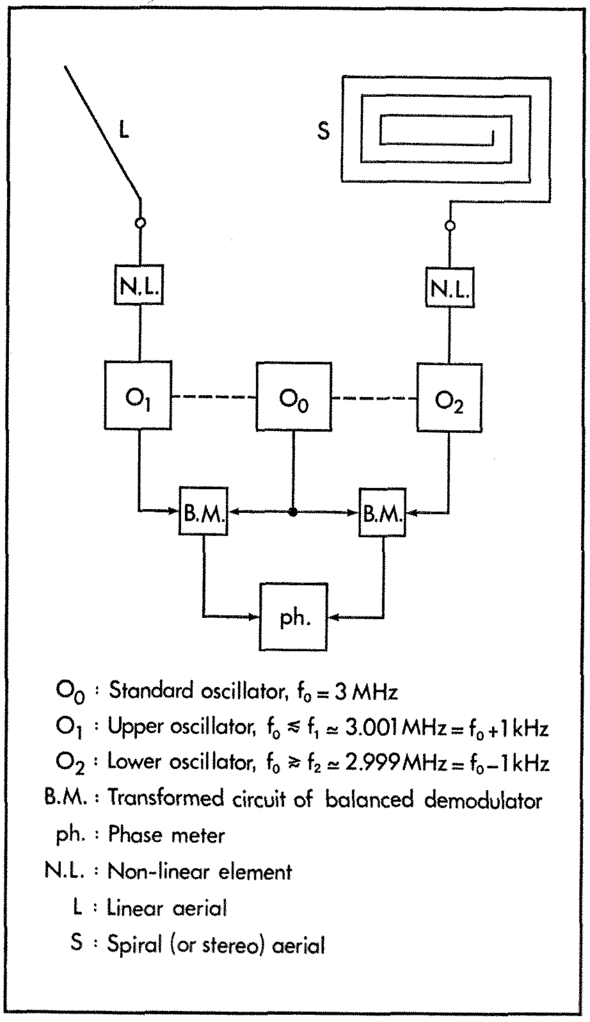


Figure 19. Block diagram of the prototype 3MHz prospecting equipment.

These two oscillators are connected to independent aerials, one of which is linear and the other is spiral as shown in Figure 19. So

$$f_1 = f_0 + 1\text{KHz} \pm \delta f_1 = 3.001 \text{ MHz} \pm \delta f_1$$

and

$$f_2 = f_0 - 1\text{KHz} \pm \delta f_2 = 2.999 \text{ MHz} \pm \delta f_1$$

where δf_1 and δf_2 can be adjusted between zero and 1KHz.

The output from the non-linear elements (Fig. 19) consists of primary beat waves of ($f_1 \pm f_0$) and ($f_0 \pm f_2$) and lower beats equal to (1KHz $\pm$ δf_1) and (1KHz $\pm$ δf_2). These beats are complex in nature and may include many harmonics.

The compound phase difference, P, between (1KHz $\pm$ δf_1) and (1KHz $\pm$ δf_2) is indicated by the phase meter and is approximately constant. When δf_1 and δf_2 are adjusted to the best condition for detection a very low frequency beat wave occurs and the compound phase difference, P, varies by only a small amount. This is represented on a chart record by a steady graph with small vertical movement (e.g. Fig. 22, Example 1).

Where Bf is the very low beat frequency, (δf — Bf) has a symmetrical distribution as shown in Figure 20 and δf_0 is the value of δf when the very low beat frequency is zero. Such a condition occurs with various combinations of δf_1 and δf_2.

These very low frequency beat waves are propagated with the complex waves formed by the transmission from the antenna. Usually when the compound phase variation (P) is small, (set by the adjustment of δf_1 and δf_2) then the equipment is operating in the optimum condition.

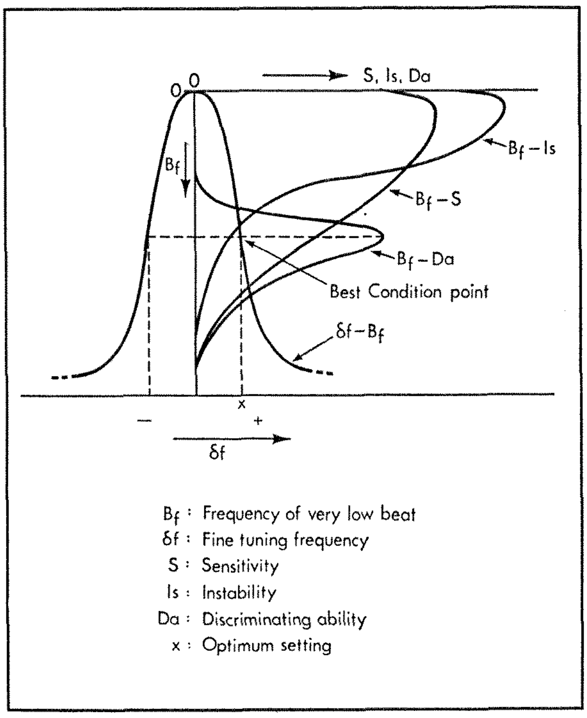


Figure 20. Optimum operating characteristics.

The propagation pattern of the transmission is shown in Figure 21. Generally the radio frequency waves are reflected at the surface or at shallow depths. As high frequency electromagnetic waves are strongly attenuated in conductive media, they rarely penetrate to a buried target. On the other hand the mixed beat wave is less attenuated and can penetrate to considerable depths, particularly as it contains very low frequency components.

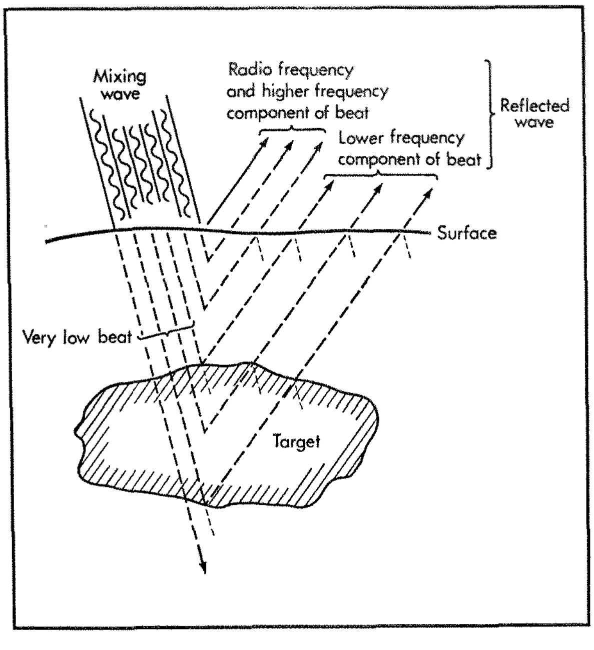


Figure 21. Propagating pattern of mixing wave.

When the beat wave is reflected from any target material it undergoes a change in phase, and the reflected wave is mixed with, and interferes with, the transmitted complex wave. The composite of the two is put into separate tank circuits on both aerials, and the resultant is a slightly modified, very low compound beat frequency. This compound frequency is either slightly higher, or slightly lower, than the original very low beat frequency. In the case where it is slightly higher, the phase difference is not as great as when the resultant frequency is lower than the original very low beat frequency. Thus the sensitivity increases when the very low beat frequency is modified to a lower compound frequency. The waves of high frequency and the higher harmonics are reduced with balanced demodulation and so rarely influence the compound phase difference. The phase meter measures a difference in compound phase between the two sides of the equipment, and this difference is recorded on a chart.

For effective detection the target material should contrast strongly with the host rock in the following properties: conductivity, permittivity, permeability, and density. The strongest reflection of the signal will occur when these properties are much greater in the target than in the surrounding rock. The order of phase deviation will differ according to the composition of the target. The method can be used even if the noise level is larger than the signal level, provided that the signal level is greater than the minimum sensitivity of the equipment.

Figure 22 shows the responses expected from the equipment in normal traversing. In Example 1, where there is no anomalous material beneath the section, the width of the chart trace of the compound phase deviation is nearly constant. Inhomogeneities in the rocks may sometimes cause minor variations in the trace. Example 2 shows the expected response of a near-spherical anomalous body. In this case the response occurs immediately above the target. When the body dips, or is of an irregular shape, the type of response is as shown in Example 3, and may be offset a short distance from the true position of the body due to interference or imperfect reflection of the signal. The same response may occur if the rock texture is markedly inhomogeneous or if the traverse is oblique to the anomalous body.

Discussion of the components in the equipment and the results obtained from Mount Azuma in Japan have been described by Kikuchi and others (1972).

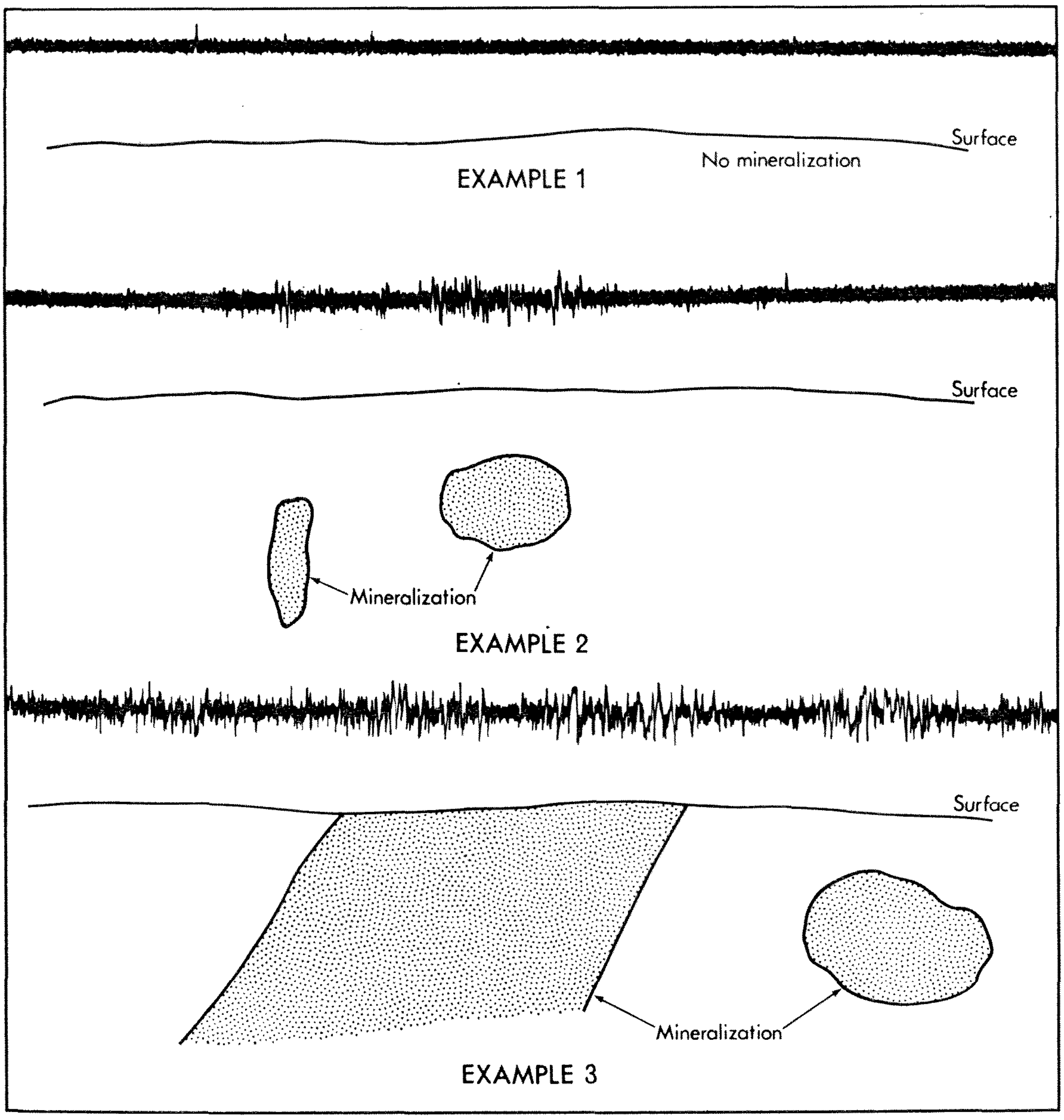


Figure 22. Examples of results.

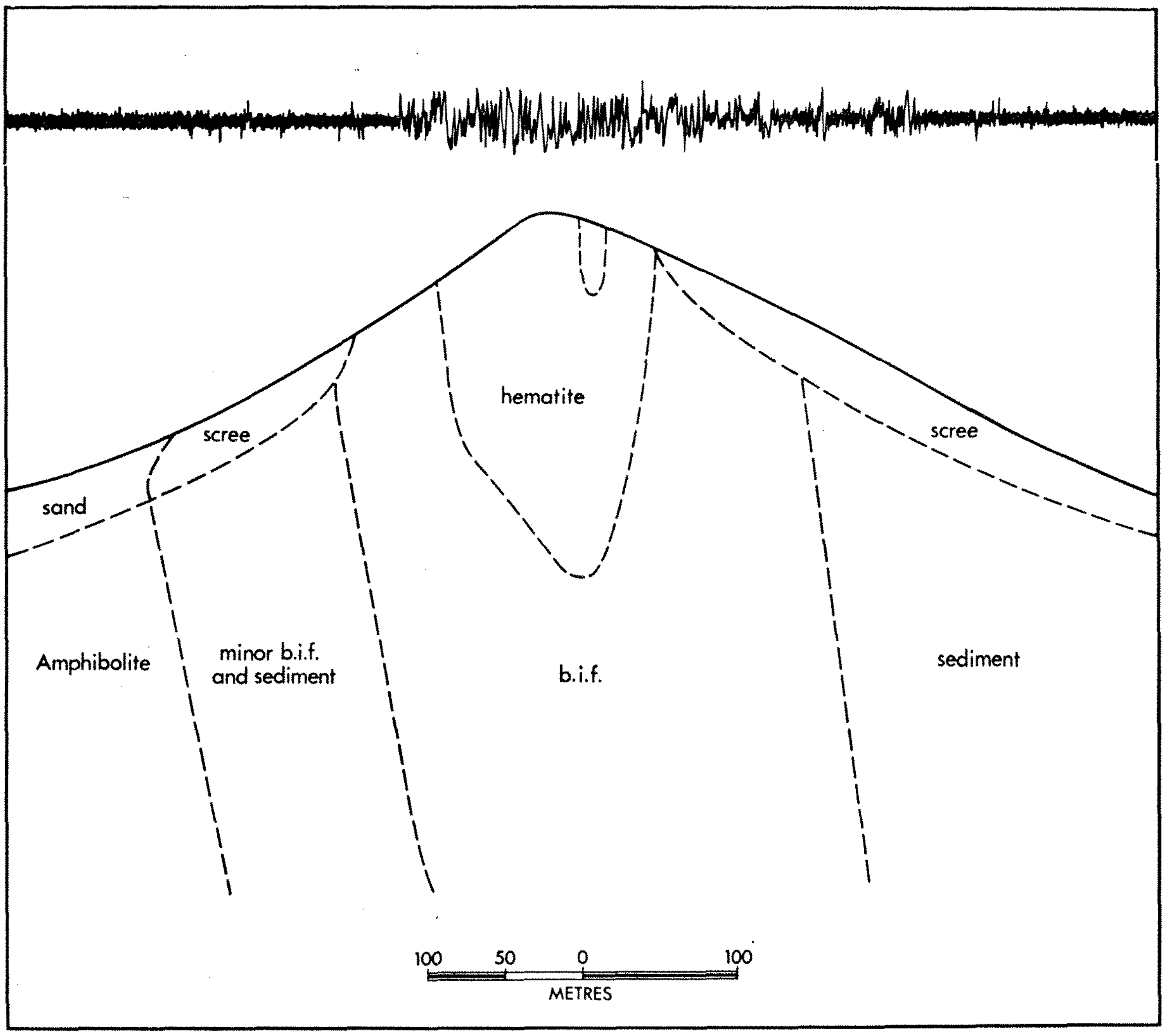


Figure 23. Area 1.

RESULTS

The following discussion of the results obtained in six of the areas tested includes a brief description of the geology of each area, but does not give all of the information that is available.

AREA 1

Geology

The traverse in Area 1 was over a sequence of steeply dipping banded iron formation with fine-grained sediments and amphibolite; hematite lenses occur within the banded iron formation. The hematite body tested is above the water table and is an enrichment of the iron formation. The mineralogy of the banded iron formation is hematite and quartz with minor magnetite and amphibole above the water table and magnetite and quartz with minor carbonate and amphibole below the water table, which is about 75 m below the highest point of the traverse. A geological section and the results of the traverse are shown in Figure 23.

Discussion of the results

The results obtained in this area show that the equipment responds to both banded iron formation and hematite. The chart presented shows the results when the equipment is set to the optimum operating conditions. Banded iron formation and hematite are distinguishable by the character of the trace and there is very little response over the sediments. The quality of this result is probably enhanced by the geological simplicity of the lode and the presence of highly magnetic minerals.

AREA 2

Geology

Area 2 consists of a sequence of flat-dipping basalt flows and gabbro sills with minor basic tuffaceous rocks. There are local concentrations of oxide ores of copper within the traversed section,

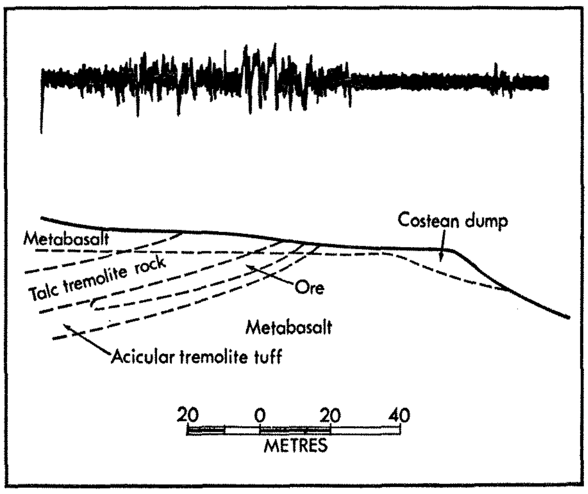


Figure 24. Area 2.

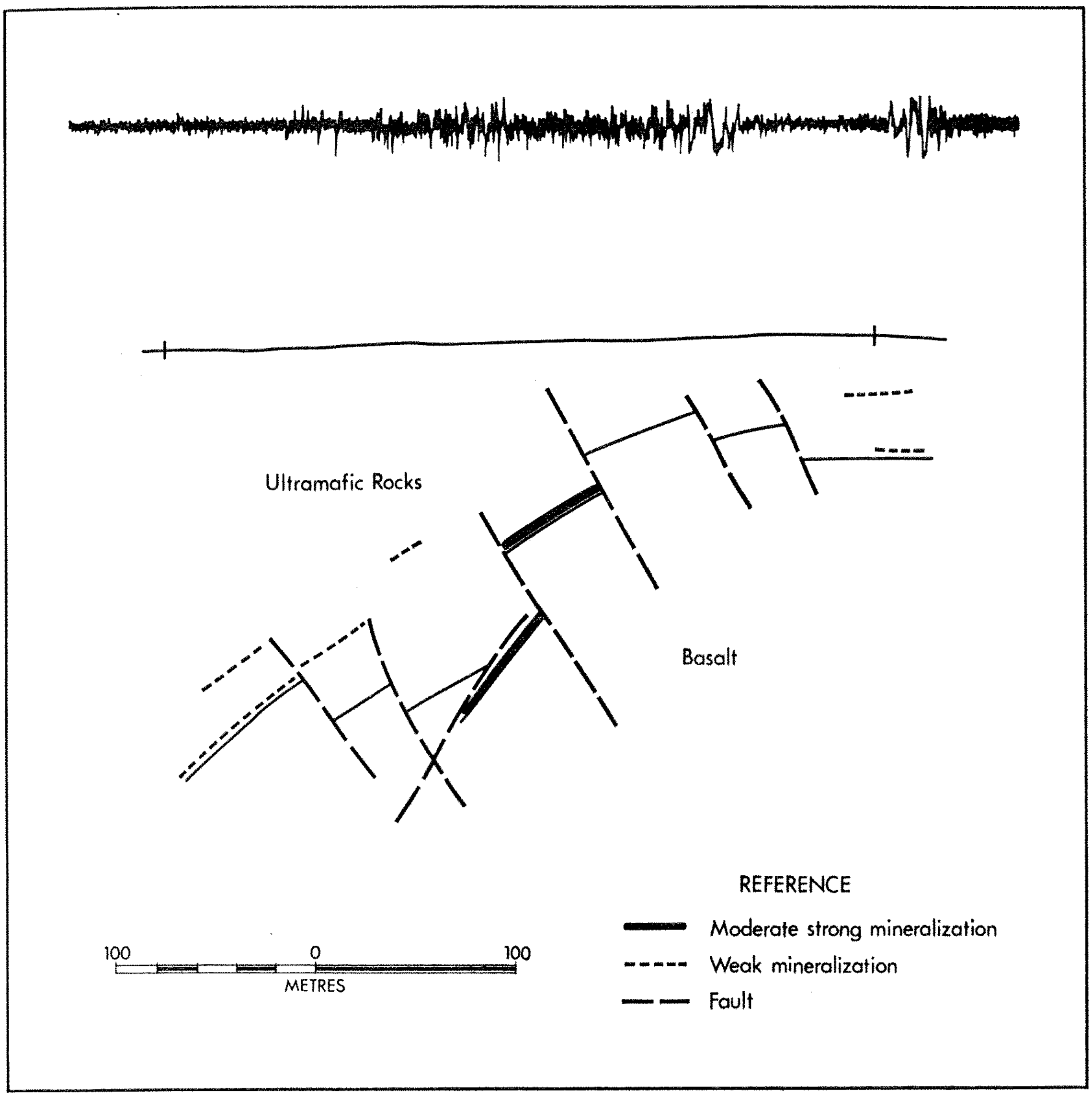


Figure 25. Area 3.

but no sulphide minerals have been reported from this deposit to date. Figure 24 shows the traverse results superimposed on the geology.

Discussion of the results

The chart indicates that the method may be able to detect oxide ores of copper. The amplitude of the trace may also indicate the presence of a deeper anomalous body, which as yet, has not been identified by other methods of prospecting. Traverses across similar geological sections in this area produced no anomalous results.

AREA 3

Geology

The host rock for the ore in Area 3 is a high-magnesian ultramafic which has been emplaced by either high-level intrusion, or extrusion. The ore consists of massive sulphides (pyrrhotite, pentlandite, chalcopyrite and pyrite) along the base of the ultramafic. There are between 1 and 10 m of highly saline, partly consolidated mud overlying weathered bed-rock in this area. The results and the geological section are presented on Figure 25.

Discussion of the results

The results obtained on this traverse show a good response over the ore body with some further reaction slightly removed from, but in the neighbourhood of the lode. The response not directly above ore zones may be related to faults. This example demonstrates that the equipment can detect anomalous bodies beneath a highly conductive layer. Effects of the latter are included in the general background noise level trace and are nearly constant.

AREA 4

Geology

A high-magnesian ultramafic rock containing massive sulphide (pentlandite, pyrrhotite, and minor chalcopyrite and pyrite) constitute the ore material in Area 4. The ultramafic has been intruded by mafic dykes and contains minor lenses of meta-sedimentary rocks. The simplified geological section and the chart from the traverse are shown on Figure 26.

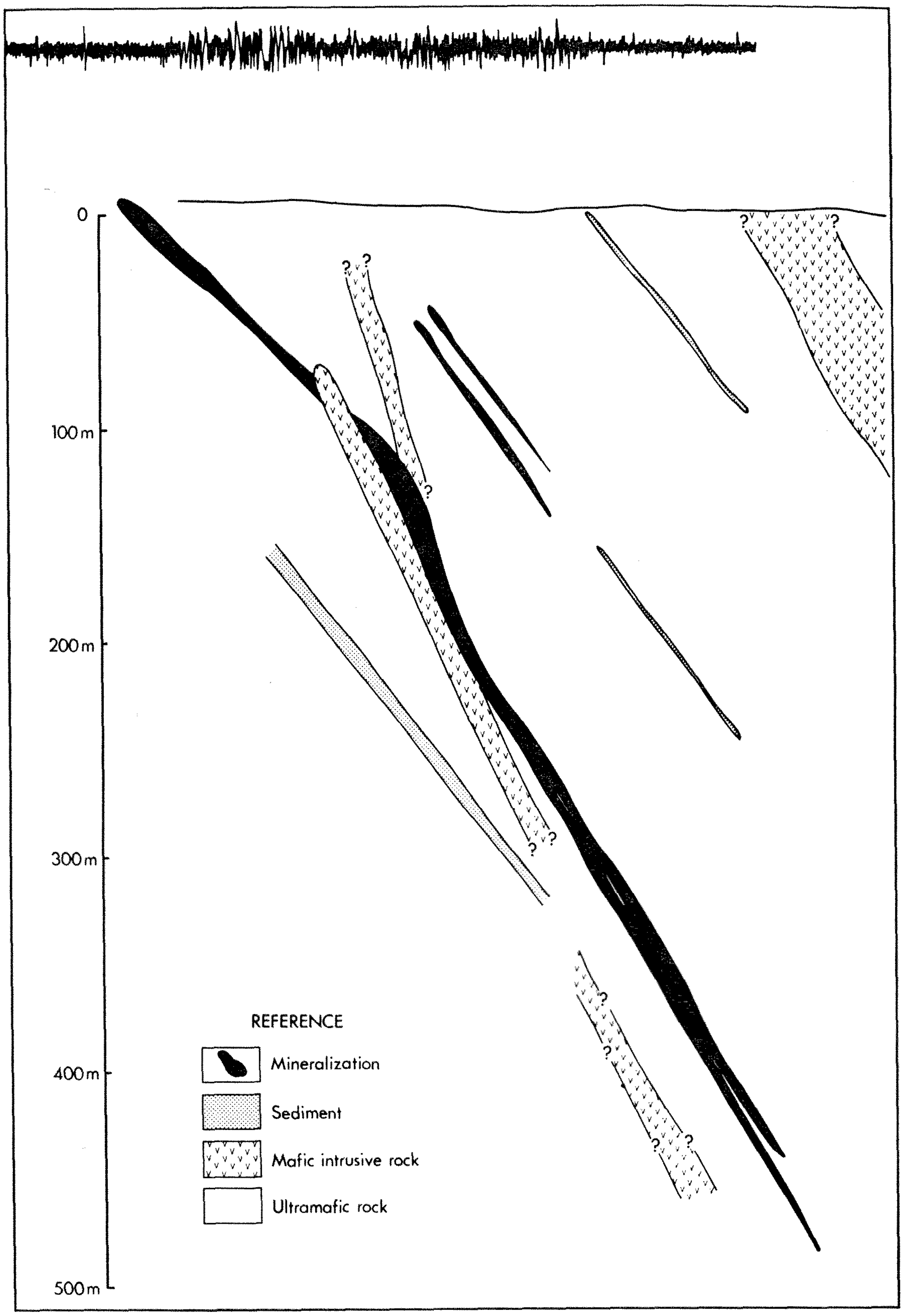


Figure 26. Area 4.

Discussion of the results

The results show the response when the instrument is adjusted to the optimum condition. The anomalies correspond well with the known distribution of ore, and indicate that detection may be possible to a depth of 300 to 500 m. A traverse oblique to this section (Watanabe and Baxter, 1972, Area F, Traverse 2) gave poor results which are interpreted as being due to the oblique traverse over the ore body, and unstable conditions within the instrument at the time of recording.

AREA 5

Geology

The host rock in Area 5 is a serpentinized pyroxenitic ultramafic rock which has a massive sulphide zone on one side, and an associated zone of disseminated sulphide mineralization. The mineralization is pentlandite and pyrrhotite with minor chalcopyrite and pyrite. The entire zone of ultramafic rocks and mineralization is enclosed in fine-grained mafic rocks which contain minor veins of quartz with chalcopyrite and pyrite. The area is covered with between 1 and 10 m of poorly consolidated sand.

Discussion of the results

The distinct response over the ore zone corresponds well with the massive sulphides (Fig. 27). The anomalous response over the mafic rocks is probably related to the veinlets of quartz and sulphide. This traverse shows that satisfactory results can be obtained over areas where there is no exposure.

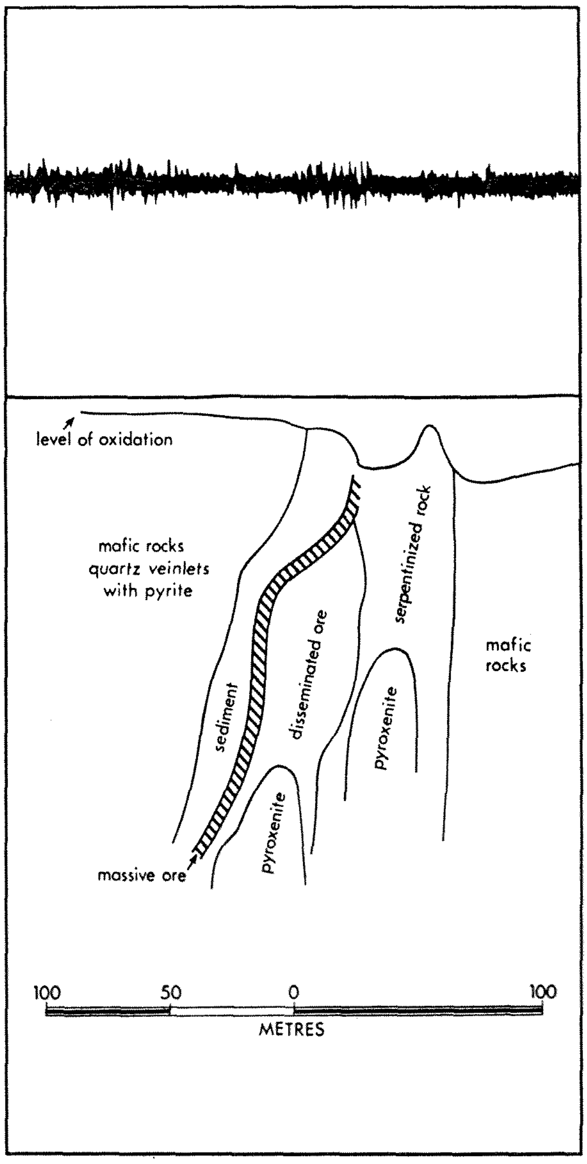


Figure 27. Area 5.

REGIONAL SURVEY

Geology

A section of the road between Scotia and Ringlock was traversed at approximately 65 km per hour to ascertain the usefulness of the method in regional geophysical reconnaissance. The results together with a map of the regional geology and the aeromagnetic contours are presented in Figure 28. West of Point A, ultramafic rocks are exposed. The remainder of the traverse has superficial rocks overlying granitic rocks to a point west of B and a succession of mafic and ultramafic rocks between C and D.

Discussion of the results

The trace obtained using this method shows that granitic rocks, mafic rocks and ultramafic rocks can be distinguished in a comparable manner to the aeromagnetic contours. It also showed that reconnaissance surveys may be carried out successfully at high vehicle speeds.

CONCLUSIONS

This prototype 3MHz electromagnetic method is easy to mount and extremely useful for rapid geophysical surveys. The results of these preliminary tests are promising and it has been demonstrated that there is a strong possibility that this method can detect hematite, oxide ores of copper, nickel sulphide, and pyrite, as well as being able to differentiate between the major rock types. The detection of disseminated molybdenite has also been demonstrated (Watanabe and Baxter, 1972).

In the current tests the entire equipment was mounted in a Landrover and surveying at speeds up to 65 km per hour gave satisfactory results. The chart used was controlled by time traversing which necessitated constant speed surveying which was difficult to maintain.

From the results obtained in Area 3 which is located on a salt lake, it is apparent that the method can obtain results through surface layers having high conductivity, where the saline layer is of fairly uniform thickness and conductivity. The adjustment of the instrument is critical and in some areas it is difficult to obtain the optimum signal to noise ratio.

Identification of the anomalous material is difficult as the response of different lode materials is similar. Estimation of the depth of the target zone is problematical as there is no consistent relationship between depth and response in the tests. These problems may be resolved and interpretation procedures placed on a quantitative basis when the method is more fully investigated.

It is possible to identify lode zones where there are separate bodies of anomalous material. This is seen in Area 4 where there is an increase in the signal strength over the subsidiary ore horizons, as well as the normal signal over the main ore horizon.

The method may prove to be of considerable value for detecting mineralized zones when they are completely covered by overburden, as in Area 5.

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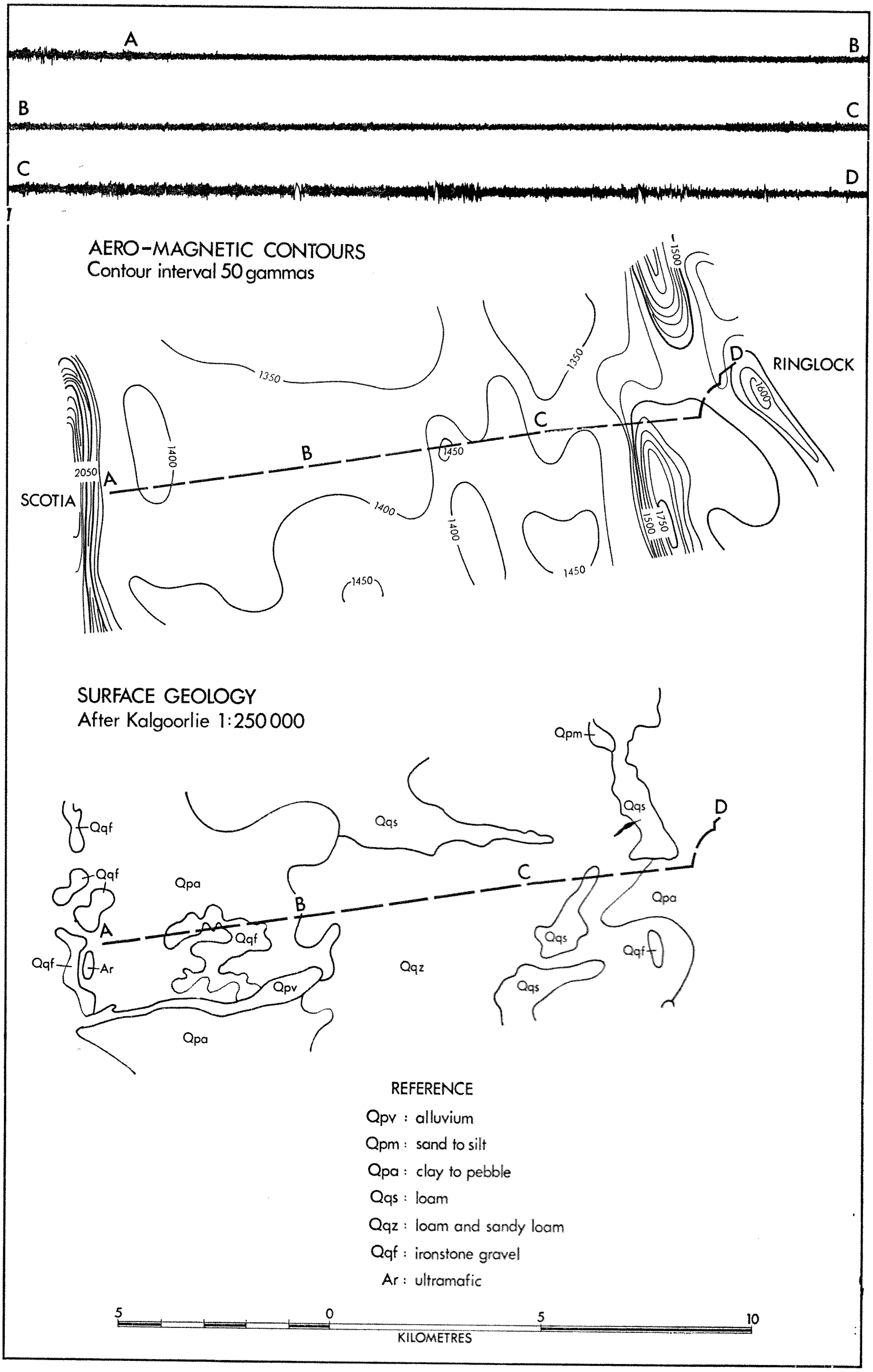


Figure 28. Regional survey.

SILICA-RICH PILLOW LAVAS NEAR SOANSVILLE, MARBLE BAR 1:250,000 SHEET

by S. L. Lipple

ABSTRACT

Excellent exposures of undeformed silica-rich pillow lavas were found during regional mapping of the Marble Bar 1 : 250,000 sheet. These closely resembled the form of basaltic pillow lavas abundant elsewhere on the sheet, but were notably hard and of siliceous appearance, with only weak carbonation. Analyses of major oxides and some trace elements are presented for two samples. These are compared with average analyses taken from the literature and, together with petrography of the samples, suggest that the pillow lavas are of rhyodacitic composition.

INTRODUCTION

During regional mapping of the Marple Bar 1 : 250,000 sheet (Hickman and Lipple, in prep.), silica-rich pillowed lavas and pyroclastics were found in a succession of Archaean basaltic volcanics, chert and ultramafic rocks. The pillowed lavas and agglomerates are excellently exposed in a gorge east of Soansville at lat. 21° 31′ 32.3″ S and long. 119° 12′ 55.7″ E along a tributary of Dalton Creek. The silica-rich pillow lavas are distinct from carbonated pillowed basalt lavas elsewhere in the area of the Marble Bar 1 : 250,000 sheet, for example those 2.5 km northwest of the Marple Bar Pool. Carbonated basaltic pillow lavas are mentioned by Noldart and Wyatt (1962), p. 109-112, and described by Finucane (1936) p.3. In the field, the pillows were noted to be light coloured, siliceous and apparently feldspathic, and were considered to be of possible rhyolitic or dacitic composition. However, subsequent studies did not clearly support this conclusion, and for the purposes of the following discussion, the pillows are described as being silica-rich or felsic. Pillow lavas of similar composition are not known to have been recorded from any other locality in Western Australia. Field mapping has suggested the existence of at least three other occurrences of similar pillow lavas, one occurrence 18 km northeast of Abydos at lat 21° 17′ 39.4″ S and long. 119° 1′ 31″ E, another 1.5 km southeast of Kelly's Copper mine at lat 21° 48′ 24.5″ S and long 119° 52′ 53.4″ E, and at 21° 55′ 15.5″ S and long. 119° 43′ 45.2″ E. However, these have not been further investigated.

GEOLOGY

GEOLOGICAL SETTING

The regional geological succession is shown in Figure 29. It consists of Archaean basaltic volcanics, partly pillow lavas, chert, rhyolitic volcanics and intrusive ultramafic rocks. The succession is folded and metamorphosed, generally to greenschist facies, but in part to amphibolite facies, and intruded by well foliated granitic rocks to the east.

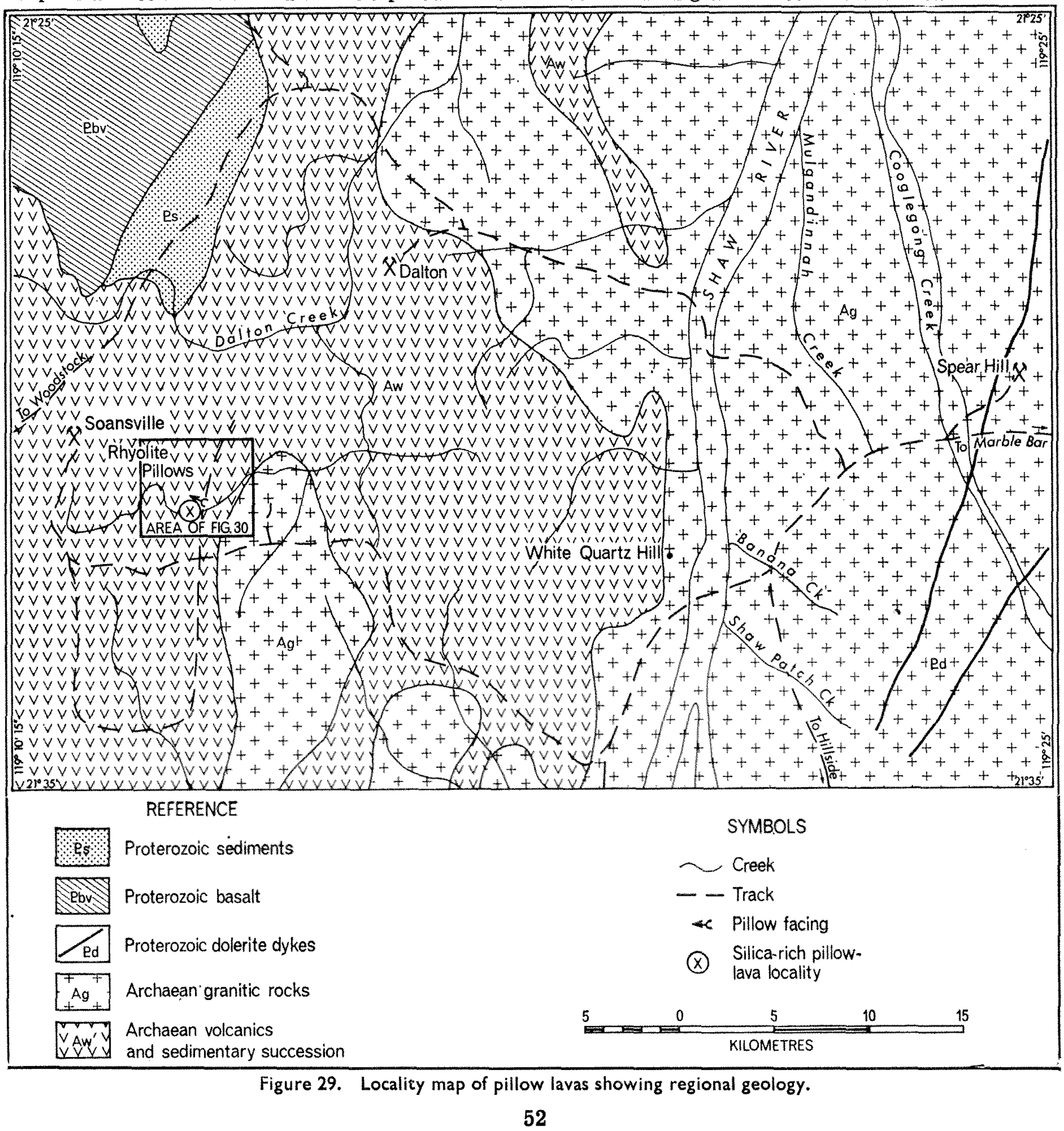


Figure 29. Locality map of pillow lavas showing regional geology.

The rocks immediately surrounding the felsic pillow lavas are shown in Figure 30. Approximate thicknesses of each unit as measured along AB in Figure 30 are shown in Table 12. The succession strikes at 030°, dips vertically or steeply west, and faces westwards, as determined by well preserved pillow structures.

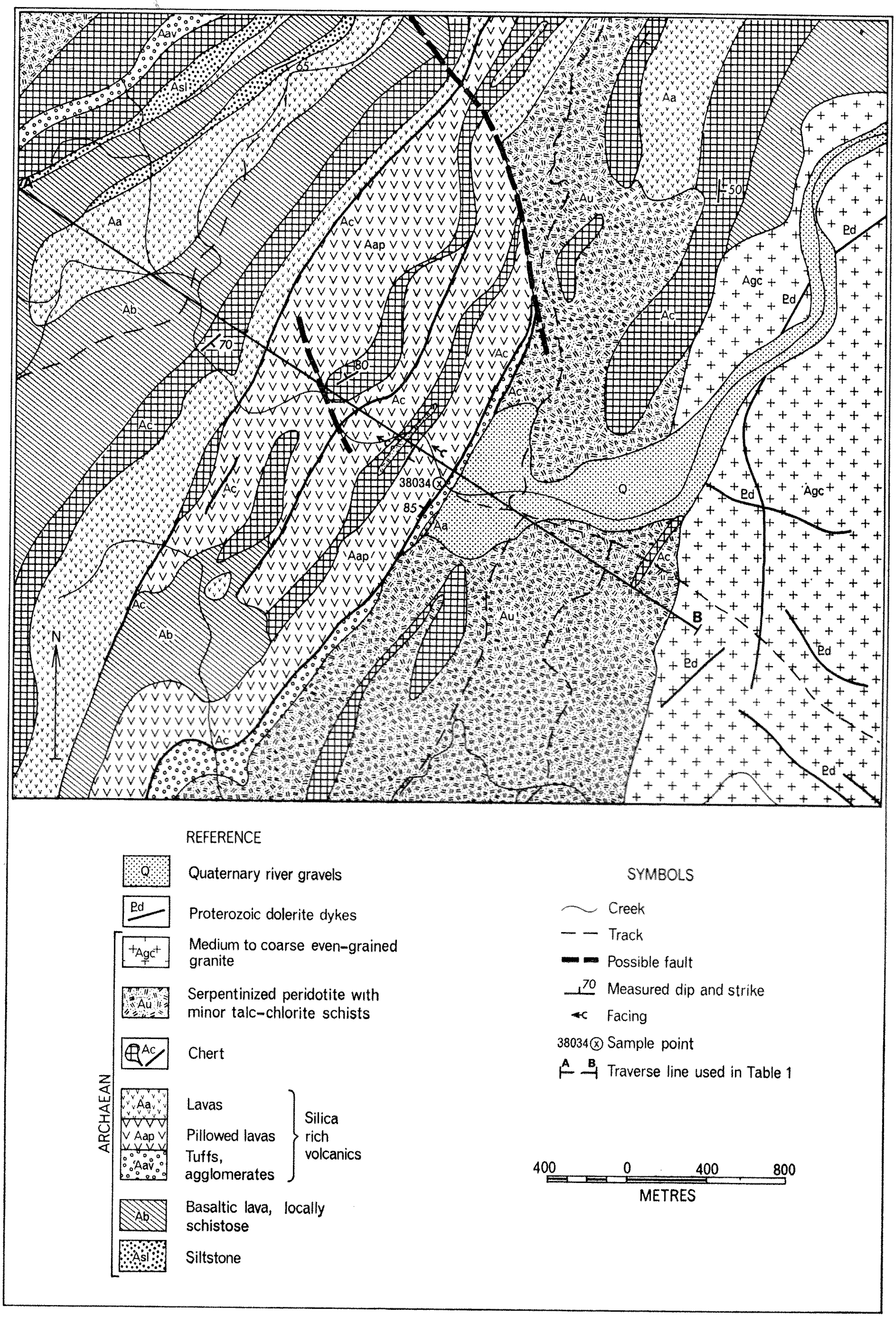


Figure 30. Detailed geological map of the area surrounding the pillow lavas.

TABLE 12. GEOLOGICAL SETTING

Map Symbol on Fig. 30	Approximate thickness metres	Description
Ab	....	Basalt
Aa	270	Silica-rich volcanics
Ab	235	Basalt, weakly schistose, fine to medium-grained, massive to weakly vesicular
Acf	140	Chert, dark-coloured, well folded
Aap	67	Silica-rich pillow lavas
Acw	5	Chert, black-coloured, massive
Aap	237	Silica-rich pillow lavas
Acw	80	Chert, dark-coloured
Aap	65	Silica-rich pillowed lavas
Acw	5	Chert, black to dark grey-coloured
Aap	118	Silica-rich pillowed lavas
Acw	2	Chert, banded grey and white-coloured
Aut	5	Ultramafic, fine-grained, soft, dark green-coloured talc-chlorite rock
Acw	3	Chert, dark, massive, vertically dipping
Aap	135	Silica-rich pillow lavas. Specimens 38034C and D
Acw	4	Chert, light grey-coloured, western margin well banded
Aav	1	Waterlain tuff, well bedded, laminated bedding, cross-bedding and possible ripple structures
Aav	30	Silica-rich agglomerate, rounded to angular vesicular rhyolite boulders in a siliceous matrix, possibly felsic glass
Aa	10	Massive grey-coloured rhyolitic lavas
Aav	5	Weathered, purple-coloured, quartz-bearing tuffs felsic
Aup	135	Ultramafic as below
Acw	20	Chert, lenticular
Aup	417	Ultramafic, as below. In part weathered to light green serpentinite pseudomorphing original peridotite texture
Acw	10	Chert, massive, lenticular recrystallized, dark grey-coloured, intruded by ultramafic
Aup	135	Ultramafic, dark-coloured serpentinite pseudomorphing fine to medium-grained olivine-rich peridotite with close-packed, granular olivines set in a pyroxene matrix
Agc		Medium to coarse even-grained biotite adamellite

The lowest layer of pillows, overlying a thin banded grey chert, has flat basal margins and convex upper surfaces (Fig. 31, B), also indicating a westward facing. Below the chert 30 m of agglomerate contains rounded to angular, fine-grained, grey-coloured, vesicular, rhyolitic fragments in a siliceous, tuffaceous (or ?glassy) matrix. The upper metre of this unit consists of well bedded, cross-bedded (west-facing) waterlain tuff. Although some fragments have sizes up to 1 x 2 cm, most are generally coarse sand sized in a finer matrix. Lamination is formed by grain-size variation. Some bands show probable ripple marking.

Below the agglomerate unit, 10 m of massive silica-rich lavas overlie at least several metres of weathered purple-coloured tuffs containing abundant quartz fragments.

DESCRIPTION OF THE PILLOWS

As shown in Figure 31, A, the pillows are well exposed and have well formed pillow structures with convex upper surfaces and concave basal margins, often with drape structures including tails. Facing determined from these structures is consistently westward. On the side of the gorge in which the pillows are exposed, they form prominent bulbous protrusions. The pillows are of variable size, frequently large, up to 4 m long and 1 m thick, but generally about 1 m long and 50 cm thick. The pillows have minor chalcedony veins. The pillow margins are very fine grained, abundantly vesicular to amygdaloidal (Fig. 31, B-D) and are light greenish-grey. The inner portions of the pillows are medium grey, fine grained, and contain chalcedony-filled vesicles elongated radially to the chilled margins. The rock is fresh and so hard that the surface cannot be scratched with a hammer. Hand specimens show only weak reaction with dilute hydrochloric acid, indicating some carbonate along thin veins but little to none within the groundmass. Colour variations within the pillow appear to correspond to areas of alteration seen in thin section. Minor pyrite is present.

The interpillow material (Fig. 31, C, D) is a mixture of massive grey chert and felsic tuff. The chert is thought to have been injected into the interstitial positions as the still plastic pillows burrowed down through poorly consolidated chert onto a consolidated pillow layer below. Some chert may have been precipitated simultaneously with the accumulation of pillows from silica-charged seawater.

Local brecciation of pillows occurs adjacent to a pod of massive grey chert. This hyaloclasite grades rapidly into unbroken pillows. There are minor layers of massive lava. All the pillows observed were non-variolitic. The possibility that the pillowform structures were actually spheroids developed in subaerial felsic lava is discounted by the presence of well formed drape features or tails in the pillows, which together with convex tops give consistent facing. Chilled vesicular margins, and a flat bottomed basal layer of pillows adjacent to banded chert also indicate a pillow, rather than a spheriod origin.

PETROGRAPHY OF THE PILLOWS

In thin section, the pillow lavas exhibit well preserved microporphyritic, hyalopilitic, amygdaloidal and spherulitic textures. Numerous rounded to irregular and elongate vesicles were infilled with a very fine-grained mosaic of chalcedony around the margins grading inward into polygonal masses of radiating fibrous fans of chalcedony. Some vesicles contain small cores of coarser anhedral quartz, and others consist entirely of a fine, massive mosaic of chalcedony.

Microporphyritic texture in the rock is exhibited by microphenocrysts of euhedral to subhedral plagioclase, in part sericitized, set either singly or in clusters in a brown coloured groundmass of crystallites which are in turn set in a nearly cryptocrystalline matrix (Fig. 32, A). The plagioclase is too fine for convenient optical determination, but X-ray diffraction examination of material from 38034D shows the presence of sodic plagioclase, possibly oligoclase. Rare patches of a fine-grained mosaic of feldspar embayed by chlorite have a euhedral outline and may pseudomorph calcic plagioclase microphenocrysts.

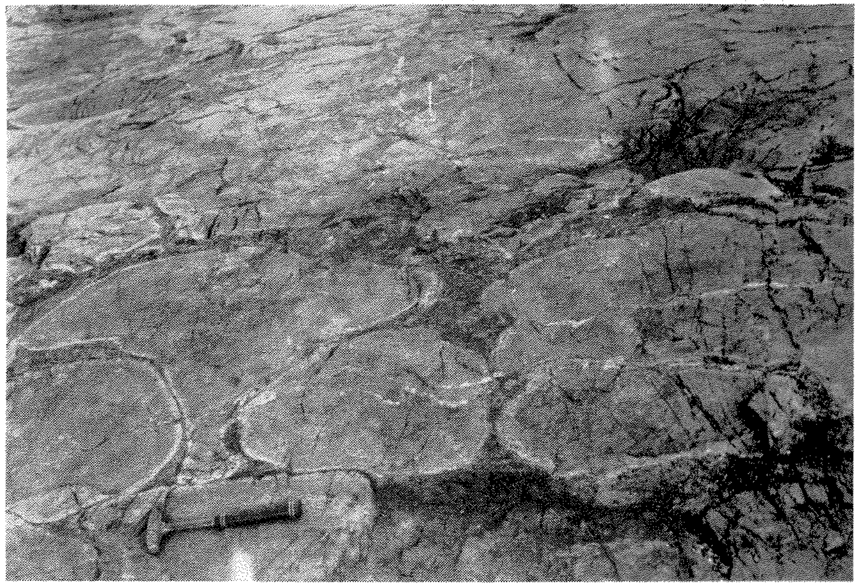
The groundmass consists of elongate feldspar crystallites (0.25 mm long) forming a relict hyalopilitic texture with an almost cryptocrystalline interstitial matrix (Fig. 32, D), which is thought to result from devitrification of glass. Near some vesicles, the crystallites appear to be moderately flow aligned. At higher magnification, the interstitial material is seen to consist of a very fine-grained mosaic of feldspar and quartz, and to contain small anhedral granules of leucoxene.

Portions of the cryptocrystalline matrix appear to have been devitrified from glass, forming numerous well developed microlites locally joined together in bow-tie manner to form spherulitic

FIGURE 31 (opposite)
Photographs of felsic pillow lavas

A West-facing pillows showing convex tops and tail structures.
B Small pillow in basal layer of pillow lavas overlying banded and partially mobilized chert.
C Amygdaloidal, chilled, light coloured pillow margins. Some dark interpillow chert and tuff.
D Amygdales elongate to pillow margins. Chalcedony veins intruding the pillows. Dark tuffaceous, cherty interpillow matrix.

Figure 31



A

B

C

D

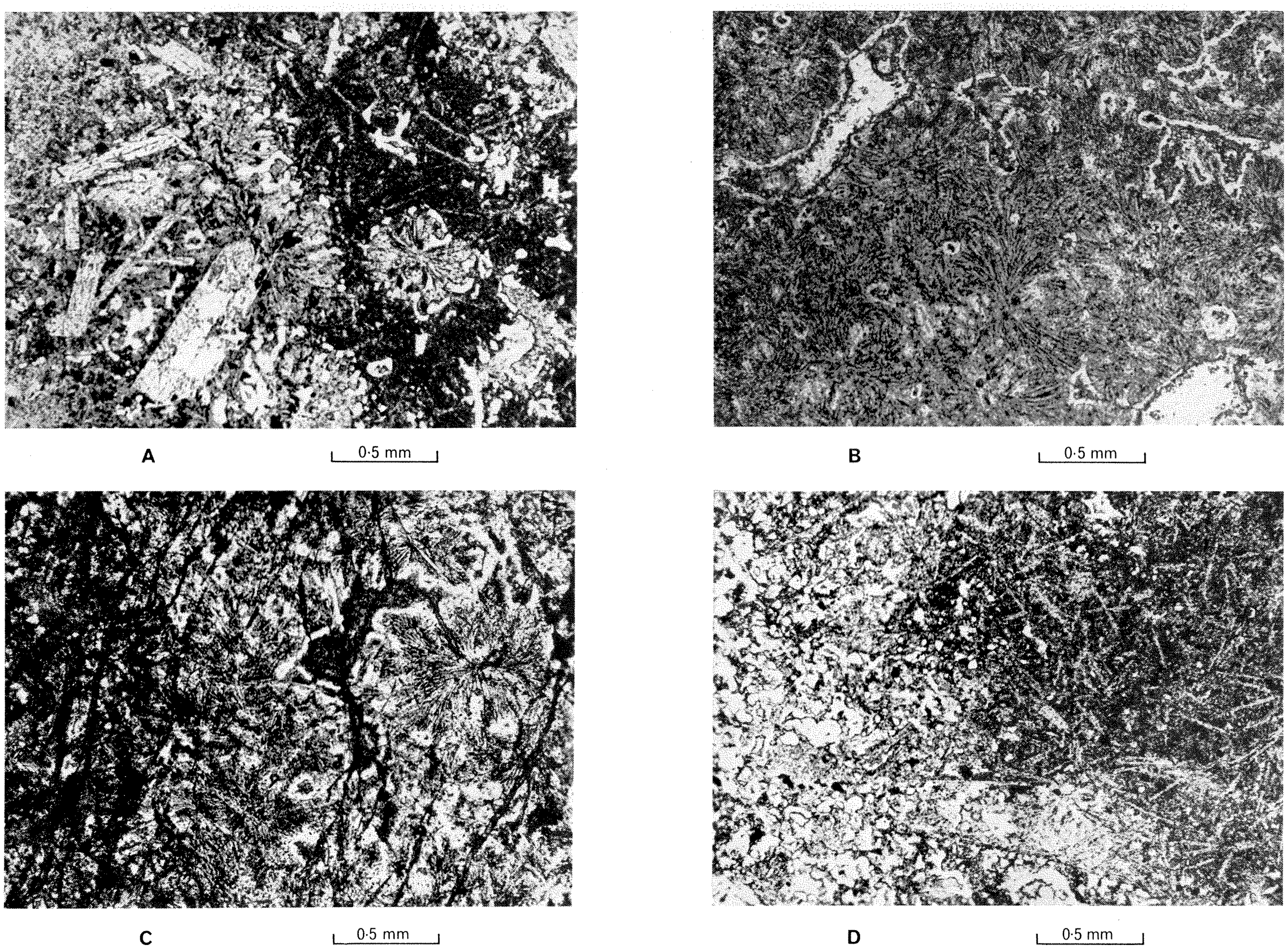


Figure 32

FIGURE 32 (opposite)

Photomicrographs of felsic pillow lavas in plain polarized light

A Plagioclase phenocrysts and crystallites.
B Chalcedony-filled amygdales and spherulitic texture.
C Spherulitic structure with interstitial cryptocrystalline material.
D Crystallites (right) and prehnite alteration (white patches on left).

masses (Fig. 32, B, C). The microlites consist of thin, elongate, curved needles. Between the microlite bundles are small irregular patches with margins of clear mosaic quartz and central areas of fine-grained, massive, felted or fibrous actinolite, probably also after glass (Fig. 32, B). The spherulitic content is variable. Both microlites and spherulites are composed of colourless feldspar. Some microlites are skeletal with numerous short projections of apparently similar composition growing orthogonally from the margins into the matrix.

Accessory minerals include abundant leucoxene and sphene, and minor magnetite. Some cubic iron sulphide, bronze coloured in reflected light, occurs within the larger chalcedony veins. Since no exsolution was observed, the mineral is probably pyrite. Although sulphide observed in hand specimens apparently occurred in the groundmass, its occurrence in the four thin sections examined was restricted to chalcedony veins.

The thin sections contain several veins which penetrate and embay the rock, and consist of massive or fan-shaped chalcedony with central lenses of anhedral granular unstrained quartz in part. These veins are truncated and offset by later calcite veins which sometimes include prehnite and chlorite. Some of the chalcedony veins terminate at vesicles.

The degree of alteration is variable. Some plagioclase microphenocrysts are colourless and unaltered, while others are partially replaced by prehnite and/or sericite and rarely by calcite. Possible relics of calcic plagioclase microphenocrysts are embayed by chlorite. Part of the glassy area has originally been replaced by chlorite which appears to have altered to fine fibrous actinolite. An apparently subhedral area of chlorite resembles a pseudomorph of poikilitic (feldspar inclusions) mafic microphenocryst.

Moderate amounts of secondary prehnite (Fig. 32, D) embay the groundmass, and clusters of apparently separate granules show simultaneous extinction. Prehnite alteration corresponds to colour variations seen on a polished hand specimen surface, and is greater towards the margins of the pillows. Vesicle infillings of fine-grained, massive mosaic chalcedony show minor replacement by calcite, and chalcedony veins have minor vermicular replacement by prehnite.

The probable alteration history was broadly: devitrification of glass and formation of spherulites; development of sericite, chlorite and conversion of ilmenite to leucoxene and possibly sphene; formation of chalcedony veins; and subsequent development of calcite, prehnite and actinolite.

The abundance of feldspar microphenocrysts, crystallites and microlites, cryptocrystalline feldspar-quartz matrix, and paucity of mafic minerals supports field observations that the pillow lavas are of felsic composition.

CHEMICAL COMPOSITION

Two fresh samples, 38034C and D, from the same silica-rich pillow were chemically analysed for major oxides (Table 13) and trace elements (Table 13B). The samples were collected 4 and 7 cm from the pillow margins, respectively. Columns 1 and 2 of Table 13 list the original analyses of 38034C and D. Column 3 is the mean of the two analyses.

TABLE 13. CHEMICAL COMPOSITIONS OF SILICA-RICH PILLOW LAVAS AND COMPARISON WITH PUBLISHED AVERAGES OF RHYOLITE, DACITE, ANDESITE AND BASALT

Major Oxide (%)	38034C	38034D	Mean						Rhyo-lite	Calc-Alkali Rhyo lite	Alkali Rhyo-lite	Dacite	Rhyo-dacite	Dacite	Ande-site	Tholei-itic Basalt
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	67·7	71·0	69·4	68·7	69·8	71·4	54·2	50·8	73·43	73·66	74·57	64·27	66·27	63·58	54·20	50·83
Al_2O_3	12·9	12·9	12·9	13·2	13·4	13·7	20·4	21·9	13·54	13·45	12·58	16·87	15·39	16·67	17·17	14·07
Fe_2O_3	1·1	0·3	0·7	0·7	0·7	0·7	1·1	1·2	1·01	1·25	1·30	3·13	2·14	2·24	3·48	2·28
FeO*	5·36	1·88	3·62	3·69	3·75	3·83	5·73	6·15	0·36	0·75	1·02	2·01	2·23	3·00	5·49	9·00
MgO	2·6	0·9	1·8	1·8	1·8	1·9	2·8	3·0	0·26	0·32	0·11	1·85	1·57	2·12	4·36	6·34
CaO	3·06	4·46	3·76	3·84	3·90	3·99	5·95	6·39	0·77	1·13	0·61	4·63	3·68	5·53	7·92	10·42
Na_2O	0·11	3·36	1·74	1·78	1·81	1·85	2·75	2·96	2·25	2·99	4·13	3·97	4·13	3·98	3·67	2·23
K_2O	2·3	1·2	1·8	1·8	1·8	1·9	2·8	3·0	6·45	5·35	4·73	1·68	3·01	1·40	1·11	0·82
H_2O+*	2·89	0·99	1·94	1·98	2·01	....	3·07	3·30	} 1·52	0·78	0·66	{ 1·20	0·68	0·56	0·86	0·91
H_2O-*	0·19	0·11	0·15	0·15	0·16	....	....	....	}			{				
CO_2*	1·53	2·16	1·85	1·89	....	....	....	....	0·01	....	....	....	....	....	....	....
TiO_2	0·54	0·54	0·54	0·55	0·56	0·57	0·85	0·92	0·10	0·22	0·17	0·38	0·66	0·64	1·31	2·03
P_2O_5	0·03	0·06	0·05	0·05	0·05	0·05	0·08	0·09	0·02	0·07	0·07	0·08	0·17	0·17	0·28	0·23
MnO	0·28	0·11	0·20	0·20	0·21	0·21	0·32	0·34	0·02	0·03	0·05	0·06	0·07	0·11	0·15	0·18
Totals	100·6	100·0	100·5	100·3	100·0	100·0	100·0	100·0	100·05†	100·0	100·0	100·20‡	100·0	100·0	100·0	100·0

KEY TO COLUMNS :

1. Original analysis of 38034C
2. Original analysis of 38034D
3. Mean of (1) and (2)
4. (3) recalculated to remove 2 per cent chalcedony veining
5. (4) recalculated to 100·0 per cent, removing CO_2
6. (4) recalculated to 100·0 per cent, removing CO_2, H_2O+ and H_2O-
7. (4) recalculated to 100·0 per cent, removing CO_2 and H_2O-, and removing 15·2 per cent SiO_2 to simulate an average andesite
8. (4) recalculated to 100·0 per cent, removing CO_2 and H_2O-, and removing 18·5 per cent SiO_2 to simulate an average basalt
9. Average of 26 rhyolites from Johannsen, 1932, p. 265, Table 132
10. Average of 22 calc-alkali rhyolites and rhyolite-obsidians from Nockolds, 1954, p. 1012, Table 1, Column II
11. Average of 21 alkali rhyolites and rhyolite-obsidians, *ibid.*, Column IV
12. Average of 19 dacites from Johannsen, 1932, p. 398, Table 197a
13. Average of 115 rhyodacites and rhyodacite-obsidians from Nockolds, 1954, p. 1014-1015, Table 2, Column IV
14. Average of 50 dacites, *ibid.*, Column VI
15. Average of 49 andesites, *ibid.*, p. 1019, Table 6, Column II
16. Average of 137 normal tholeiitic basalts, *ibid.*, p. 1020, Table 7, Column VII

* For 38034C and D, analysis by chemical methods (Analyst E. J. Tovey). All other analyses by X-ray fluorescence techniques (Analyst N. L. Marsh

† Also 0·02 per cent each of SO_3, BaO and S, and 0·25 per cent FeS_2

‡ Rest 0·07 per cent

TABLE 13A. C.I.P.W. NORMS OF SILICA-RICH PILLOW LAVAS

Norm Mineral	38034C		38034D		Mean	
	1	2	3	4	5	6
Quartz	48·19	44·44	40·89	35·76	44·22	39·44
Corundum	8·28	4·96	3·11	0·00	5·66	1·47
Orthoclase	13·59	14·77	7·09	7·68	10·64	11·23
Albite	0·93	1·02	28·43	30·04	14·72	15·65
Anorthite	5·31	15·93	8·08	17·34	6·63	19·47
Diopside	0·00	0·00	0·00	4·68	0·00	0·00
Wollastonite (D)	0·00	0·00	0·00	2·35	0·00	0·00
Enstatite (D)	0·00	0·00	0·00	1·12	0·00	0·00
Ferrosilite (D)	0·00	0·00	0·00	1·21	0·00	0·00
Hypersthene	15·04	16·07	4·76	2·86	10·03	10·64
Enstatite (H)	6·47	6·97	2·24	1·37	4·48	4·73
Ferrosilite (H)	8·56	9·09	2·52	1·48	5·55	5·90
Magnetite	1·59	1·74	0·43	0·43	1·01	1·01
Ilmenite	1·03	1·08	1·03	1·08	1·03	1·08
Apatite	0·07	0·07	0·14	0·14	0·12	0·12
Calcite	3·48	....	4·91	....	4·21	....

KEY TO COLUMNS:

1. 38034C Calculated from original analysis
2. 38034C Calculated volatile free and less 2 per cent silica veins
3. 38034D Calculated from original analysis
4. 38034D Calculated volatile free and less 2 per cent silica veins
5. Mean Calculated from the mean of the original analyses
6. Mean Calculated from the volatile free mean and less 2 per cent silica veins

On a polished surface of hand specimen 38034D, which was considered representative of the pillow, the area occupied by chalcedony veins was determined by measuring along a 3 mm spaced grid. The volume of veins was assumed proportional to the measured area. The densities of chalcedony and the lava are sufficiently similar that no significant error resulted when the mass of chalcedony, estimated at being 2 per cent of the rock, was subtracted from the silica component in the mean. This was recalculated to the original total (Table 13, Column 4). Other modifications to remove carbon dioxide and total volatiles as shown in Table 13, Columns 5 and 6 were also made. The norms calculated on the original analyses, their mean, and recalculated volatile-free analyses are presented in Table 13A.

For comparison, eight average analyses taken from Johannsen (1932, p. 265 and p. 398) and Nockolds (1954, p. 1012-1020) are given for rhyolite, rhyodacite, dacite, andesite and tholeiitic basalt. Comparison of Column 16 in Table 13 with the present analyses shows that the latter are not of basaltic composition. To determine whether the pillow lavas may be silicified andesite or basalt, silica in the mean was reduced to that of the average andesite and tholeiitic basalt (Table 13, Columns 15 and 16), and the other components recalculated to make a total of 100.0 per cent (Table 13, Columns 7 and 8). Even subtraction of 15 per cent silica produces a result which has more alumina, potash, ferrous iron, manganese and combined water, and less ferric iron, magnesia, lime, soda, titanium and phosphorus than average andesite. Relative to average basalt, the pillow lava after subtraction of 19 per cent silica has more alumina, potash, soda, manganese and combined water, and less ferric iron, ferrous iron, magnesia, lime, phosphorus and titanium. Although this comparison does not prove that the pillow lava is not silicified basalt or andesite, it does indicate that if the present composition of the pillow lavas is due to metasomatism, the processes are very complex and the silica-rich pillow lavas are not the result of simple silicification of pillowed andesite or basalt.

Apparent from Table 13, Coulmns 1 and 2, there is some disparity in the two analyses of the same pillow. This requires some explanation.

High combined water content indicates an unusual degree of post-eruptive hydration. Ewart (1971, p. 424) states that alkali leaching, especially sodium loss and oxidation of iron, are likely during hydration of volcanic glasses. This may explain the low soda and potash contents of the two samples, particularly the very low soda content of 38034C relative to 38034D. This sample was collected from near the pillow margin and has a high content of combined water. However, both samples have a high ferrous to ferric iron ratio indicating little oxidation either during hydration or devitrification of glass, and indicates the absence of weathering.

Joplin (1964, p. 151-2) states that the process of devitrification of glassy selvedges of pillow lavas shows that chemical diffusion occurs and that the devitrified glass differs chemically from the original glass and from the crystalline core. Using a series of analyses across a single pillow, Vallance (1960, p. 35-37) has shown that the selvedge is enriched in lime and ferric iron and depleted in silica and soda as a result of devitrification, and the core is concomitantly depleted in lime and ferric iron and enriched in silica and soda. With the exception of lime, these trends are observed for the two analyses presented. Ferrous iron and magnesia also appear to be enriched in the sample nearest the selvedge.

Recent studies by Ewart (1971) on rhyolite lavas support the conclusion that devitrification results in chemical redistribution in the lavas.

Although the overall lime and magnesia contents of the silica-rich pillow lavas may have been modified during hydration or later metasomatism, it seems unlikely that extensive alumina, iron, titanium, phosphorus or manganese metasomatism would occur. Metasomatism of andesitic or basaltic pillow lavas to produce the silica-rich pillow lavas therefore seems improbable, and certainly complex if it did occur. Although only two samples were analysed, comparison of the mean with averages from the literature suggests a rhyodacitic composion, with possibly some leaching of alkalis.

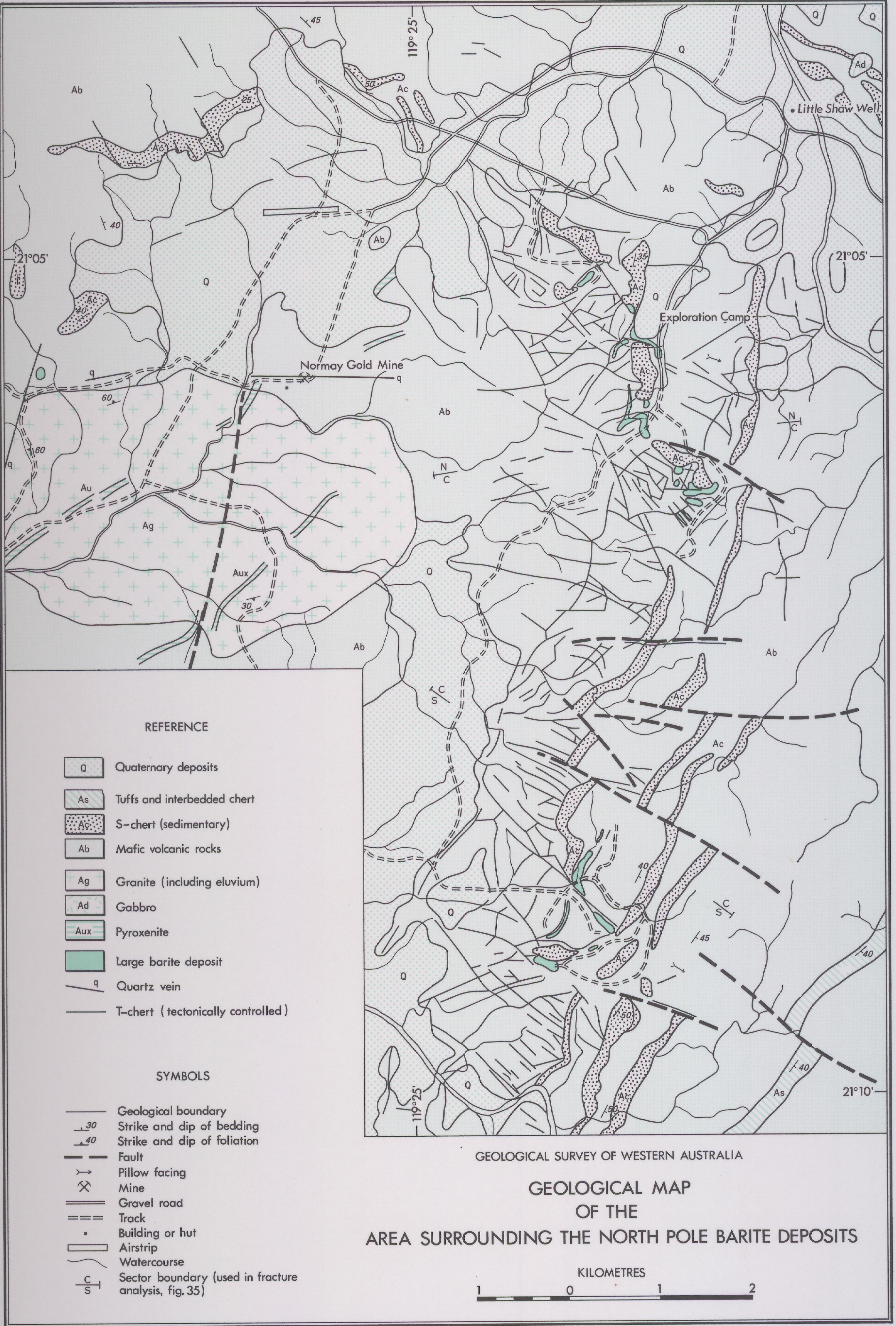
Consideration of the average norm of the samples (Table 13) favours a dacitic composition with normative orthoclase forming 24 per cent of the total feldspar, and the normative plagioclase being sodic labradorite, An_{55}. The presence of hypersthene in the norm does not detract from the description of the pillow lavas as rhyodacitic or dacitic, since the average dacite given in Table 13, Column 14, from Nockolds (1954, p. 1015) when treated by the same norm programme as the mean in Table 13A, Column 6, contains 7 per cent normative hypersthene. In addition, Joplin (1964, p. 164-5) describes dacites containing hypersthene phenocrysts which are commonly quite fresh even though hornblende and biotite phenocrysts show resorption. Williams and others (1955, p. 123-4) describe dacites containing modal hypersthene and regard the average composition of plagioclase, both porphyritic and microlitic as calcic andesine, An_{50}.

Comparison of average trace element data in the literature for igneous rocks with the trace element data presented in Table 13B supports a rhyodacitic or dacitic composition for the silica-rich pillow lavas. References used were Wedepohl (1970) for La, Sn and Rb; Goldschmidt (1954) for Ba, Cu, Pb, W, Ni, Cr and Sr; Hawkes and Webb (1955) for Ba, Cu, Li, Pb, Sn, Cr, Zn and Ni; Ewart, Taylor and Capp (1968) for Rb, Ba, Sr, and Li; Ewart and Stipp (1968) for Rb and Sr; and Rankama and Sahama (1950) for Cu, Li, Pb, Sr and Ni.

TABLE 13B. TRACE ELEMENT ANALYSES OF SILICA-RICH PILLOW LAVAS (in ppm)

Trace Element	38034C	38034D	Average C & D
Ba	430	260	345
Cu*	130	90	110
Li	30	<10	15–20
Pb	20	20	20
Sn	7	5	6
Rb	150	120	135
Sr	15	70	43
W	10	<5	5–7
Ni*	130	50	90
Cr*	110	140	125
Zn*	310	100	205
Zr	30	35	33

* Analyses by chemical methods (Analyst E. J. Tovey)
Other elements by X.R.F. (Analyst N. L. Marsh)



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GEOLOGICAL MAP
OF THE
AREA SURROUNDING THE NORTH POLE BARITE DEPOSITS
KILOMETRES
1
0
1
2
REFERENCE
Q Quaternary deposits
As Tuffs and interbedded chert
Ac S–chert (sedimentary)
Ab Mafic volcanic rocks
Ag Granite (including eluvium)
Ad Gabbro
Aux Pyroxenite
Large barite deposit
q Quartz vein
T–chert (tectonically controlled)
SYMBOLS
Geological boundary
30 Strike and dip of bedding
40 Strike and dip of foliation
Fault
Pillow facing
Mine
Gravel road
Track
Building or hut
Airstrip
Watercourse
C S Sector boundary (used in fracture analysis, fig. 35)
119°25'
21°05'
21°10'
Little Shaw Well
Exploration Camp
Normay Gold Mine
Ab
Q
Ac
Ad
Au
Ag
Aux
As
q
N C
S C
45
25
50
40
60
35
30

Figure 33

Concentrations of barium, lead, tin, rubidium and tungsten favour a felsic composition rather than andesite or basalt. Lithium is higher than the average for basaltic rocks. However, the concentrations of nickel and chromium favour an original andesitic composition for the pillow lavas although Joplin (1964, p. 166) presents analyses for a dacite and rhyodacite with 400 ppm and 800 ppm nickel oxide respectively. High copper and zinc concentrations which would appear to indicate a basaltic composition may have been concentrated by accessory pyrite occurring in the samples.

CONCLUSION

Chemical analysis and petrographic investigation show that the pillow lavas are of silica-rich and feldspathic composition. They are probably not silicified basaltic pillow lavas and certainly not carbonated basaltic pillow lavas. More analyses would be required to determine an exact composition of the pillows, with consideration of the variation noted by Vallance (1960, p. 35-37; 1969, p. 10-15) and others.

There are thought to be at least three other occurrences of silica-rich pillow lavas on the Marble Bar 1 : 250,000 sheet similar to the one studied. Since light-coloured pillow lavas in the Pilbara have been previously considered to be carbonated basaltic pillow lavas, these should be closely examined. If the suggestion that the silica-rich pillow lavas are rhyodacitic is correct, then this study demonstrates (a) that pillows may develop in lavas of rhyolite to dacite composition and (b) that such volcanics may occur in a subaqueous environment in the Pilbara Block. A subaqueous environment for this locality is further suggested by interpillow chert and palaeocurrent structures in the underlying volcanogenic sediments. Because of the current search of felsic volcanics for base metal deposits, the existence of siliceous submarine lavas deserves further investigation, since these indicate an environment suitable for the development of stratiform ore deposits (Stanton, 1960; 1961).

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THE NORTH POLE BARITE DEPOSITS, PILBARA GOLDFIELD

by A. H. Hickman

ABSTRACT

The largest known barite deposits in Western Australia occur at North Pole, 40 km west of Marble Bar. The barite, which occurs within a greenstone sequence of chert and mafic lavas, originated as an Archaean sedimentary deposit. During Archaean diastrophism this bedded barite was partially forced into the radial-concentric fracture system of a large dome.

The North Pole deposits are well positioned to supply oil exploration companies working on the continental shelf off northwestern Australia, and could also greatly increase Australian exports of the mineral. An exploration programme is being conducted to determine mining feasibility.

INTRODUCTION

In 1912 T. Blatchford of the Geological Survey reported a large lode of barite to the southeast of the North Pole Gold Mining Centre, 40 km west of Marble Bar. Though impressed by the size and purity of the deposits, Blatchford (1912) stated that inaccessibility and limited demand would preclude mining. In recent years, however, rapidly expanding markets and improved mining methods have meant that extraction of the mineral must now be viewed as a potential commercial proposition. Associated Minerals Pty. Ltd. currently hold Mineral Claims 45/1008, 1102, 1418, 1519-23, 1604-05 and 6462 covering most of the area's known deposits and Dresser Australia Pty. Ltd. are conducting a drilling programme to obtain an accurate estimate of reserves. Preliminary geological investigations by Dresser have indicated barite reserves of several million tonnes.

Prospecting, road construction, drilling and sampling are currently continuing at the prospects. In 1970, 508 t of barite were extracted.

LOCATION, ACCESS AND FACILITIES

The prospects are situated 120 km southeast of Port Hedland at Lat. 21° 06′S and Long. 119° 27′E (Fig. 33). Road access from Port Hedland is by way of the Great Northern Highway for 100 km and by graded track for a farther 55 km. An exploration camp has been established 2 km to the south of Miralga Crossing and a nearby bore drilled to a depth of 20 m maintains a good supply of water.

GEOLOGY OF NORTH POLE

The regional geology of the area around North Pole is depicted on the Marble Bar sheet of the 1 : 250,000 Geological Series (Noldart and Wyatt, 1962; Hickman and Lipple, in prep.). The barite prospects are situated within one of the Pilbara's largest Archaean greenstone belts. Most such belts are usually broadly synclinal, but at North Pole a central dome, about 35 km in diameter, is developed. Between the North Pole Mining Centre and the barite prospects, erosion of the dome has exposed a core of granite. Greenstone xenoliths in the margin of this body show it to be intrusive, though no significant structural discordance is apparent on a regional scale.

STRATIGRAPHY

The Archaean succession enveloping the granite is over 15 km in true thickness and of varied lithological composition. It is remarkably undeformed compared with similar successions in adjacent belts and has only been subjected to lower greenschist facies metamorphism.

The lower part of the stratigraphic succession is outlined in Table 14.

TABLE 14.

	Description	True thickness
	Felsic lavas and metasedimentary rocks	
5	Mafic pillow lavas with some chert and agglomerate bands	6 km
4	Tuff, chert and metasedimentary rocks	0·5 km
3	Mafic lavas with some chert and metasedimentary rocks	5 km
2	Thick chert interbedded with mafic lavas	1·5 km
	Barite deposits	
1	Mafic lavas (oldest)	2 km
	Granite (intrusive)	

Apart from testifying to the subaqueous deposition of the succession, the widespread occurrence of undeformed pillow structures in mafic lavas suggests that its present thickness closely approximates its original thickness.

Bedded chert ("S-chert" of Dunbar and Rogers, 1961) within the succession may have been formed by chemical precipitation. According to Turner and Verhoogen (1960, p. 261), thick beds of chert are commonly found within this type of sequence and are derived from late magmatic, silica-rich emanations. Alternatively, the chert may have originated from the weathering of volcanic ash or by the replacement of pre-existing sedimentary units. A minor part of the succession is composed of tuff, mudstone and quartzite.

Figure 33 shows that the barite deposits are all situated close to, and generally underneath, the lowest bedded chert unit of the succession. The northern and southern prospects are 8 km apart, yet between them the "mineralized belt" is no more than 0.5 km wide. Within this belt the barite is interlayered with chert, either in sub-vertical vein-like structures (Fig. 34C) or in beds which, in outcrop, appear to form part of the stratigraphic succession (Fig. 34B). About 6 km to the west of the northern prospects, another deposit shown on Figure 33 is situated at approximately the same stratigraphic level.

The origin of the barite is discussed later.

STRUCTURE

Whereas the regional distribution of the barite deposits is stratigraphically controlled, field observations reveal that structural features govern their size, shape and lateral distribution along strike. The most impressive aspect of the area around the prospects, both on the ground and on the geological map, is its box-work pattern of ramifying cherts (Fig. 34A). So numerous and closely spaced are these cherts that they form a rugged range of hills rising more than 100 m above the surrounding countryside. The barite prospects are all situated within this box work.

Folding

The North Pole area is structurally a dome. Like other granite domes of the Pilbara, this fold is surrounded by deep synclinal greenstone belts. Apart from an anticlinal extension towards the southwest, the dome is only slightly elongate about a north-northeast to south-southwest axis and generally measures about 35 km in diameter. Lower Proterozoic strata resting unconformably on the eroded surface of the fold establish it as being of Archaean age.

The geometry of the dome is somewhat complicated by what appear to be parasitic folds on its flanks. Where anticlinal, these structures contain chert box works.

At the barite prospects several interesting examples of folding occur. Interlayered barite and chert beds contain tight to isoclinal folds and, in places, mesoscopic thrusts can be seen (Fig. 34H). These structures may represent early gravitational slumping, or they could be interpreted as drag folds accompanying flexural slip during uplift of the dome. Cleavage planes within the barite are commonly slightly crenulated revealing the presence of deformation subsequent to recrystallization.

Tectonic foliation associated with the main folding is locally restricted to a biotite foliation in the granite, a weakly developed bedding plane schistosity in some of the mafic lavas and a sub-vertical strain-slip cleavage disposed radially about the eastern and southern flanks of the dome. Though rather uncommon, this latter structure is of interest since it could have been formed by circumferential compression associated with upward movements in the centre of the fold (c.f. radial folding about salt diapirs).

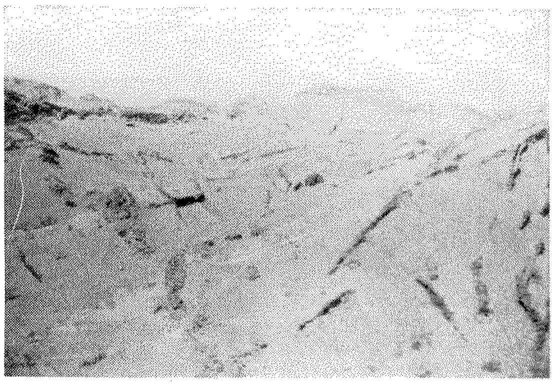
Fracture analysis

Many of the world's deposits of barite and the associated minerals fluorite, galena and sphalerite occur in fractured domes (Dunham, K. C., 1948; Wisser, 1960; Dunham, A. C., and Hanor, 1967). In describing mineral deposits of the Central United

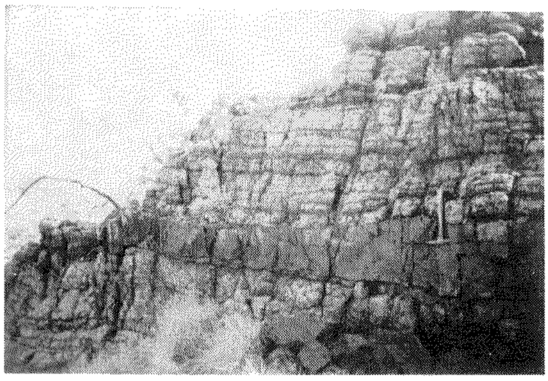
FIGURE 34 (opposite)

Photographs of structures in the barite deposits

A A chert box-work pattern near the exploration camp.
B Interbedded chert (dark) and barite (2 km south of the exploration camp).
C Vertical barite veins (light) within mafic volcanic rocks and chert (2–3 km south of the exploration camp).
D T-chert cross cutting barite layers (near exploration camp).
E Barite interlayer surface from above (near exploration camp).
F Large bulbous swelling of barite layers (near exploration camp).
G A reniform structure in interbedded barite and chert (near exploration camp).
H Isoclinal folding within the barite. Note thrust plane, right centre (near exploration camp).

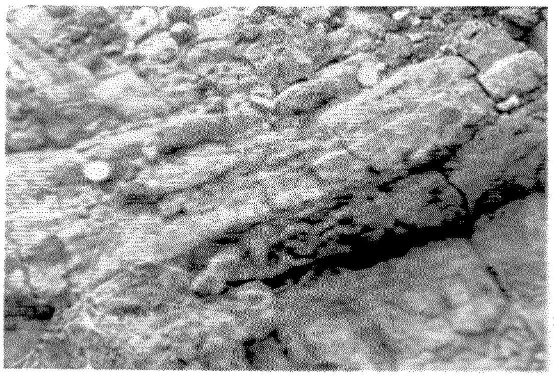


A



B

C



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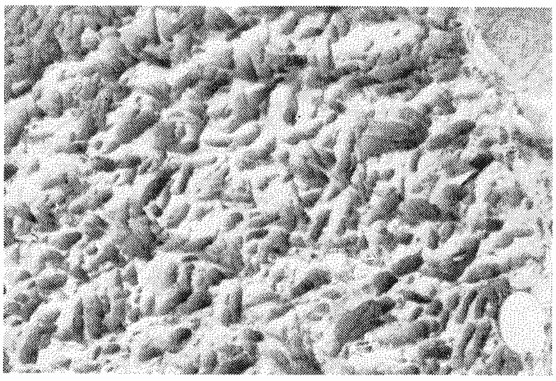

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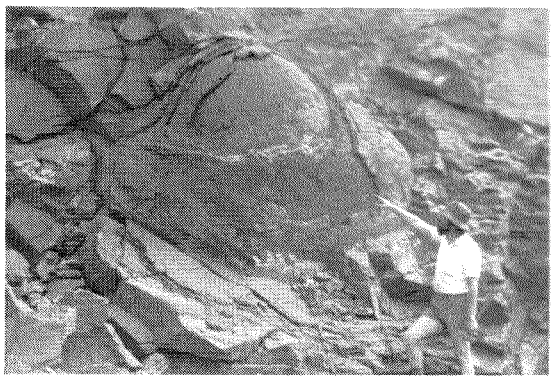
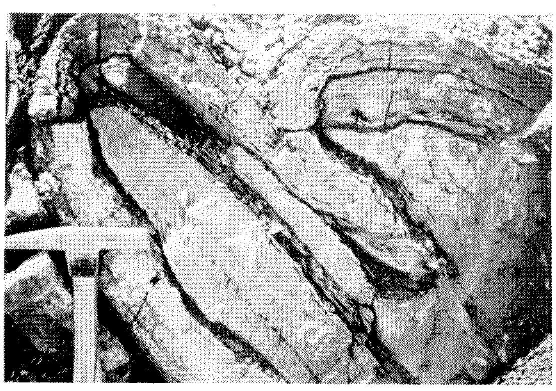


F

G



H

Figure 34

States Heyl (1968) states that "known major mineral deposits and many promising sulphide occurrences are located along complex fault systems and particularly over structural domes at intersections of fault systems". Badgley (1965) expresses the view that fracture intensity studies are important in the pin-pointing of ore bodies.

Irrespective of whether the North Pole barite is of hydrothermal or sedimentary origin, it is obvious in the field that many of the deposits now occupy veins within the fracture system of the dome. A study of this system may thus help to determine the distribution of the barite.

Air-photographs of the North Pole area reveal a well developed lineament pattern. On the ground, these features prove to be faults, joints and veins of "T-chert" (tectonically controlled chert, Dunbar and Rogers, 1961). The latter can be distinguished from S-chert (sedimentary) by their lack of internal banding, their rectilinear outcrop pattern and their typically discordant relations to adjacent strata. Intrusive in character, the T-chert has entered the dome's fracture system of joints and faults.

Figure 35 presents a statistical analysis of T-chert strike frequency in three sectors of the area shown on Figure 33. The three component diagrams of this figure reveal that the chert veins exhibit two strike maxima at about 300° and 050°. Around the flanks of the dome a radial fault system

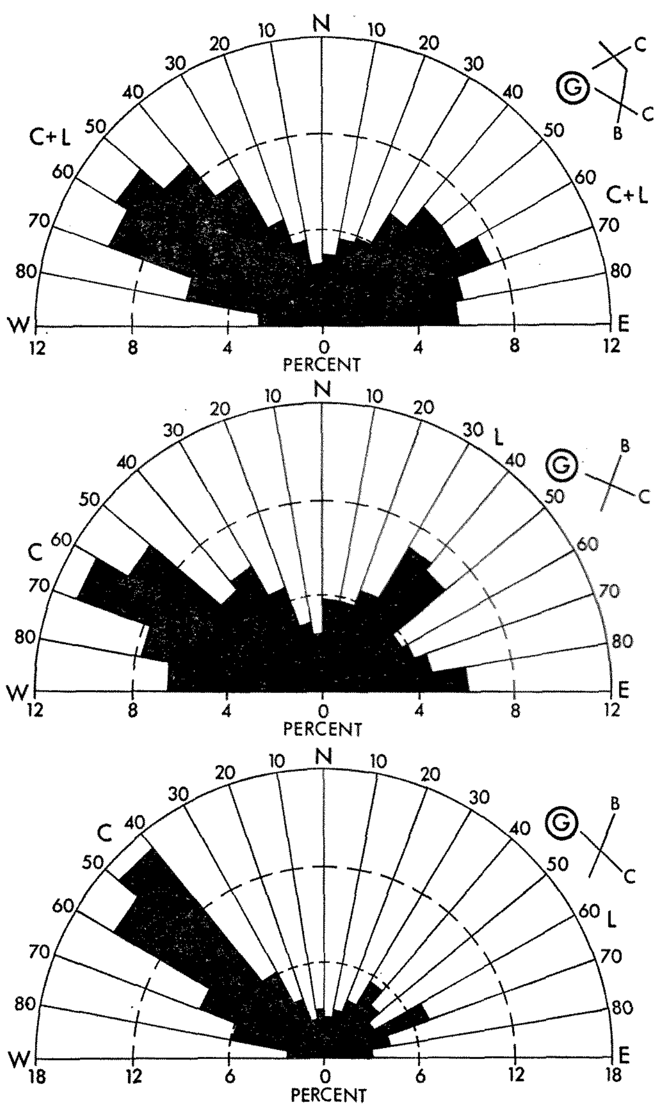


Figure 35. Strike frequency diagrams for T-chert in the area of the barite prospects

is developed but Figure 35 does not reveal any tendency towards radial orientation of T-chert bodies within the area of the prospects. This appears to be due to the presence of local folding in the northern sector. Cross fractures associated with this folding are oriented both in northeast and northwest directions according to which limbs they occupy.

Since the axis of the dome trends north-northeast, the dominant west-northwest set of T-chert veins in the central and southern sectors clearly represent cross fractures on the major structure. The east-northeast-striking T-chert veins here belong to a complementary longitudinal set.

The dome's fracture system of joints and faults must have been formed by tensional stress either during or shortly after uplift. T-chert was probably derived by the solution of S-chert in areas of maximum strain and migration of the material so obtained to regions of low pressure. Barite "veining" probably occurred at about the same time.

BARITE DEPOSITS

The barite deposits are largest at fracture intersections and in regions of minor flexure. In such areas they not uncommonly measure 20 m in width and may be over 50 m long. Such ore bodies may be lenticular, tabular, wedge shaped or zigzagged according to local structure. In contrast, barite deposits within S-chert occur in tabular masses and are stratigraphically controlled. This type of barite is often closely interbedded with sedimentary chert (Fig. 34, B). The extension of such deposits at depth is more predictable than that of veins but, in general, they constitute thinner bodies.

The colour of the barite is pale blue-grey. It is coarsely crystalline and occurs in discrete layers about 10 cm to 20 cm thick. Inter-layer surfaces are composed of crystal faces which closely interlock with those of adjacent layers (Fig. 34, E); these surfaces are often slightly iron stained.

Occasionally the layers of barite are isoclinally folded and also exhibit mesoscopic reniform structures up to 2 m across (Fig. 34, F). The barite is of high grade except where mixed with chert, agate or quartz.

ORIGIN

Since the deposits are strongly folded and injected by Archaean T-chert (Fig. 34, D), they must be of Archaean age. This point is emphasized by the degree of stratigraphic control over the positioning of the ore bodies.

Three possible origins should be considered for the North Pole barite deposits:

(1) Formation by the replacement of pre-existing sediments

(2) Precipitation from hydrothermal solutions

(3) Deposition as bedded sedimentary barite

Replacement is a selective process and it might reasonably be expected that relics of the original lithology would remain had the deposits been formed in this way. No such relics have been observed.

Hydrothermal ore bodies take many forms. It could be argued that the layered nature of the barite originates from spasmodic crustification and that the deposits conformable with bedded chert testify to lateral veining. Under such a hypothesis, the stratigraphic control exerted on the barite's distribution might be due to restriction of the upward migrating solutions beneath a thick chert. A chert does exist along, and generally above, the line of barite prospects, and this is the lowest major chert of the succession. Ore fluids could have entered the area during, or shortly after, the emplacement of the North Pole granite, rising through the dome's fracture system to reach the present level of the deposits.

Weighted against the hypothesis of hydrothermal veining are several strong arguments in favour of a sedimentary origin:

(1) Where least deformed, the barite occurs in layers structurally concordant with adjacent bedded chert and the surrounding mafic lavas

(2) The barite deposits are confined to a single stratigraphic level for 8 km along strike

(3) Individual barite layers are never observed to wedge out or cross cut; they present a bedded form

(4) The barite deposits are essentially monomineralic in composition

(5) No accompanying sulphide mineralization is present

(6) No wall-rock alteration has been observed

(7) On breaking and crushing, the barite emits a strong fœtid odour. This is also a characteristic of certain bedded barite deposits in the United States (Mills and others, 1971)

(8) Interlayered barite and chert are considerably folded

(9) The barite-chert association is common in sedimentary barite deposits (Perry and others, 1971).

It is concluded that the North Pole barite deposits are probably of sedimentary origin. During uplift of the North Pole dome they constituted a mechanically active layer and were much folded and ruptured. Joints and faults belonging to the dome's fracture system were locally invaded by diapiric folds of the bedded barite.

GRADE AND ORE RESERVES

The grade of the main deposits, as estimated from surface inspection and sampling, is high, although in certain cases the barite is contaminated with chert. Due to local complexities of structure, all the prospects must be carefully tested before any reliable estimate of reserves can be obtained. Surface outcrops indicate that the deposits are the largest in Western Australia and possibly in Australia. The area's regional structure suggests that the mineralization belt dips westwards from the prospects at about 40°. A surface gravity survey might help to provide an indication of barite reserves at depth.

CONCLUSIONS

The North Pole barite deposits are the largest yet discovered in Western Australia and, if current testing by Dresser Australia Pty. Ltd. yields favourable results, production at a rate of 50,800 t per year could both supply the oil exploration companies working on the continental shelf off northwestern Australia and take advantage of overseas markets in Indonesia Papua-New Guinea and South East Asia.

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THE PETROLOGY OF AN ULTRAMAFIC LAVA NEAR MURPHY WELL, EASTERN GOLDFIELDS, WESTERN AUSTRALIA

by J. D. Lewis and I. R. Williams

ABSTRACT

A partially serpentinized olivine peridotite lava flow from Murphy Well, 185 km north-northeast of Kalgoorlie, is 162 m thick and is mainly a porphyritic peridotite containing about 60 per cent euhedral olivine crystals set in a matrix of acicular diopsidic clinopyroxene and devitrified glass. A flow top 21 m thick contains amygdales and dendritic olivine crystals in a matrix of clinopyroxene and glass. Serpentinization is partial and original igneous textures have been preserved.

Chemical and modal analyses are presented which show that there has been no differentiation either by gravity after extrusion or flow differentiation during extrusion. It is thought that the magma was extruded as a mobile, essentially crystal-free liquid, supersaturated in volatiles.

Electron probe analyses indicate a forsteritic olivine (Fo_{90-93}) and an alumina-rich clinopyroxene in the range salite-calcic augite. Probe analysis of the devitrified glass and other evidence support the hypothesis that serpentinization involved only local redistribution of elements.

A consideration of the morphology of the amygdales shows that the dendritic olivine of the flow top crystallized from a liquid which remained mobile until much of the olivine had crystallized out.

INTRODUCTION

The concept of an essentially liquid ultramafic magma being emplaced high in the earth's crust or extruded as a lava has recently been revived by geologists in Canada, South Africa and Western Australia (Naldrett and Mason, 1968; Viljoen and Viljoen, 1969a; Nesbitt, 1971) to explain spinifex textured (i.e. quench textured) peridotites observed in Archaean greenstone belts. The "crystal mush" hypothesis of Bowen (1928) does not explain such rocks and recent writers suggest a magma with 20 per cent or less olivine crystals and an ultramafic liquid fraction capable of crystallizing a peridotite containing about 40 per cent olivine.

The purpose of the present paper is to describe an ultramafic body from Yundamindra Station, 185 km north-northeast of Kalgoorlie which the authors believe to be a peridotite lava extruded as an essentially crystal-free liquid. The rocks are of Archaean age and several flows are involved in a small, relatively poorly exposed area of about 1 km². Only a single flow unit, 162 m thick, will be described in this report. The exposure is 12 km southeast of Yundamindra homestead and access is gained from the station track linking Murphy Well with Bore Well (Fig. 36). The sample area lies about 100 m south of the track on the gentle southeast slope of a low ridge.

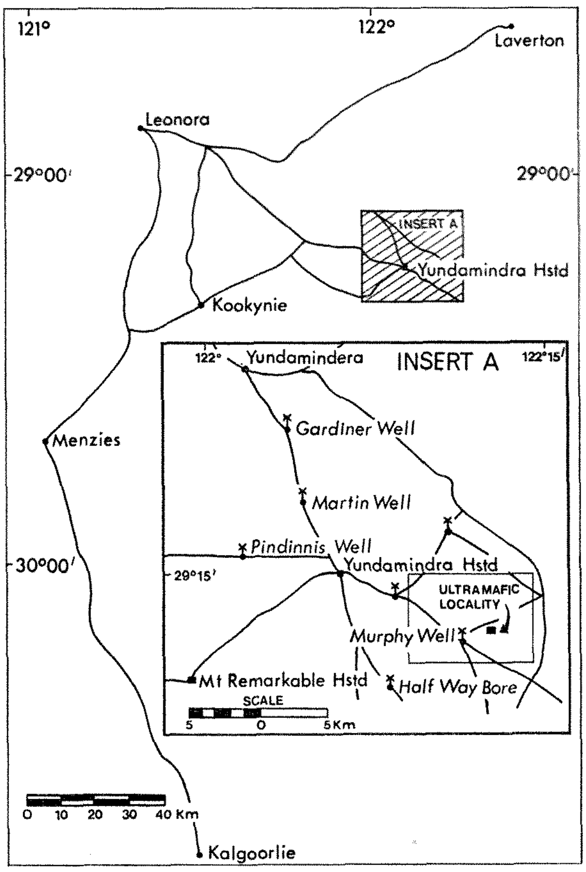

Figure 36. Locality map Murphy Well ultramafic body

The exposure was mapped by C. F. Gower in 1970 during the course of regional mapping on the Edjudina 1 : 250,000 sheet and the regional geology has been described by Williams and others (1971).

GENERAL GEOLOGY

The metamorphosed layered succession in the Murphy Well area (Fig. 37) is part of the largely mafic Morelands Formation. It is overlain 5 km east of Murphy Well by mixed felsic and clastic rocks of the Gindalbie Formation. Three kilometres west of Murphy Well the Morelands Formation has been intruded by a biotite granite pluton with a metamorphic aureole up to 1 km wide.

The Morelands Formation in this area consists mainly of regionally metamorphosed, tholeiitic basalts together with metamorphosed extrusive ultramafic and ultrabasic rocks. The ultramafic rocks, including the Murphy Well ultramafic body, are peridotites and high-magnesian basalts. The formation also contains metamorphosed, homogeneous dolerite and gabbro, layered gabbro and serpentinized extrusive peridotite and dunite bodies which are believed to be co-magmatic and concomitant with the extrusive mafic and ultramafic rocks. Minor cherts, fine-grained clastic and felsic rocks make up the remainder of the Morelands Formation. Laterite and jasperoidal cappings are common on the ultramafic rocks.

The Morelands Formation has been tightly folded into south-plunging isoclinal structures and the regional dip is vertical to steeply east. The Murphy Well ultramafite is believed to be on the eastern limb of a south-plunging syncline.

The Honman Fault, a large dislocation zone marked by a prominent line of quartz blows, trends northwesterly across the area a little south of Murphy Well. The fault has an apparent sinistral strike slip movement. A north-trending fault, with relative downthrow to the west, lies a little to the east of Murphy Well.

THE MURPHY WELL ULTRAMAFIC LAVA

The Murphy Well ultramafic body is poorly exposed over a strike length of 500 m; it passes beneath alluvium to the south and laterite to the north. Where sampled the body dips vertically and has an estimated thickness of 162 m. The western margin (top) of the flow is marked by a conspicuous zone of amygdales and dendritic olivine up to 21 m wide. The eastern exposures of the peridotite, in contrast, consist of close-packed, medium-grained equant olivine crystals. The various textures of the rock are well displayed on weathered surfaces.

A thin (about 1 m) bed of cherty tuff marks the western boundary of the body which overlies felsic extrusive rocks. At least two further fine-grained ultramafic bodies overlie the cherty tuff but these both lack amygdaloidal peridotite with dendritic olivine.

PETROLOGY

Throughout its thickness the flow is a dense, fine-grained, blue-black, partially serpentinized peridotite. The base of the flow is marked, in parts, by a narrow zone of pale green, bleached serpentinite and the top is indicated by amygdaloidal peridotite the amygdales imparting a distinctive knobbly appearance to the rock. The mineralogy is constant throughout the thickness of the flow and consists of partially serpentinized olivine (Fo_{90-93}), fresh clinopyroxene and devitrified glass. Despite serpentinization the original textures of the rock

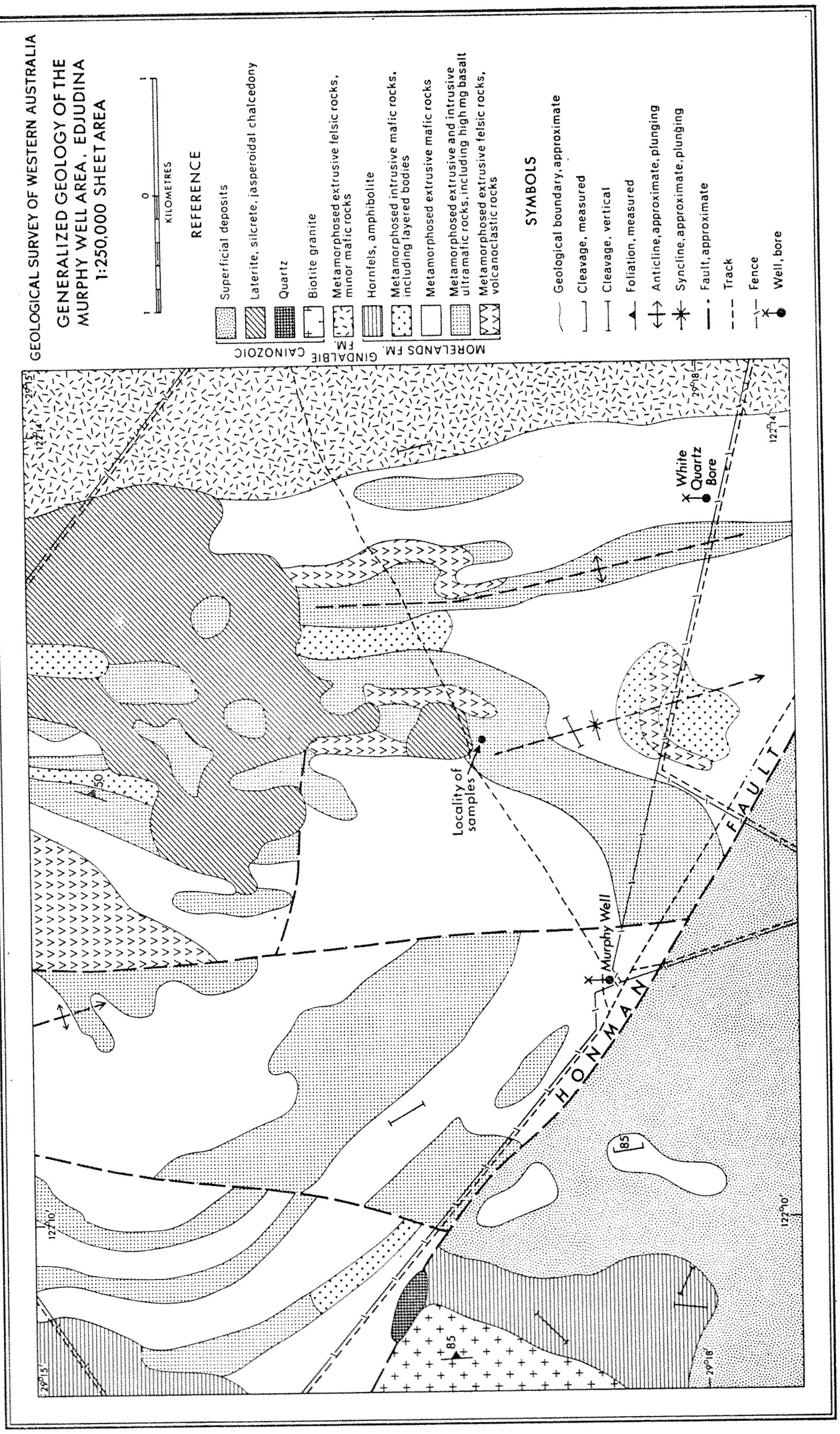

FIGURE 38 (opposite)

Photomicrographs of amygdaloidal peridotite, Murphy Well (Arrows point to top of flow).

A 26652/A Amygdale showing pyroxene-rich tail and an upward projection. To the right of the amygdale is a plumose olivine crystal.

B 26652/A Well developed amygdale and pyroxene tail showing zonation chlorite and calcite filling the vesicle and an arc of magnetite grains within the tail indicating a former position of the amygdale.

C 26652 Small amygdale and dendritic olivine. The skeletal olivine grains are in optical continuity throughout much of the photograph.

D 26652/A Plumose olivine grains showing a directional texture.

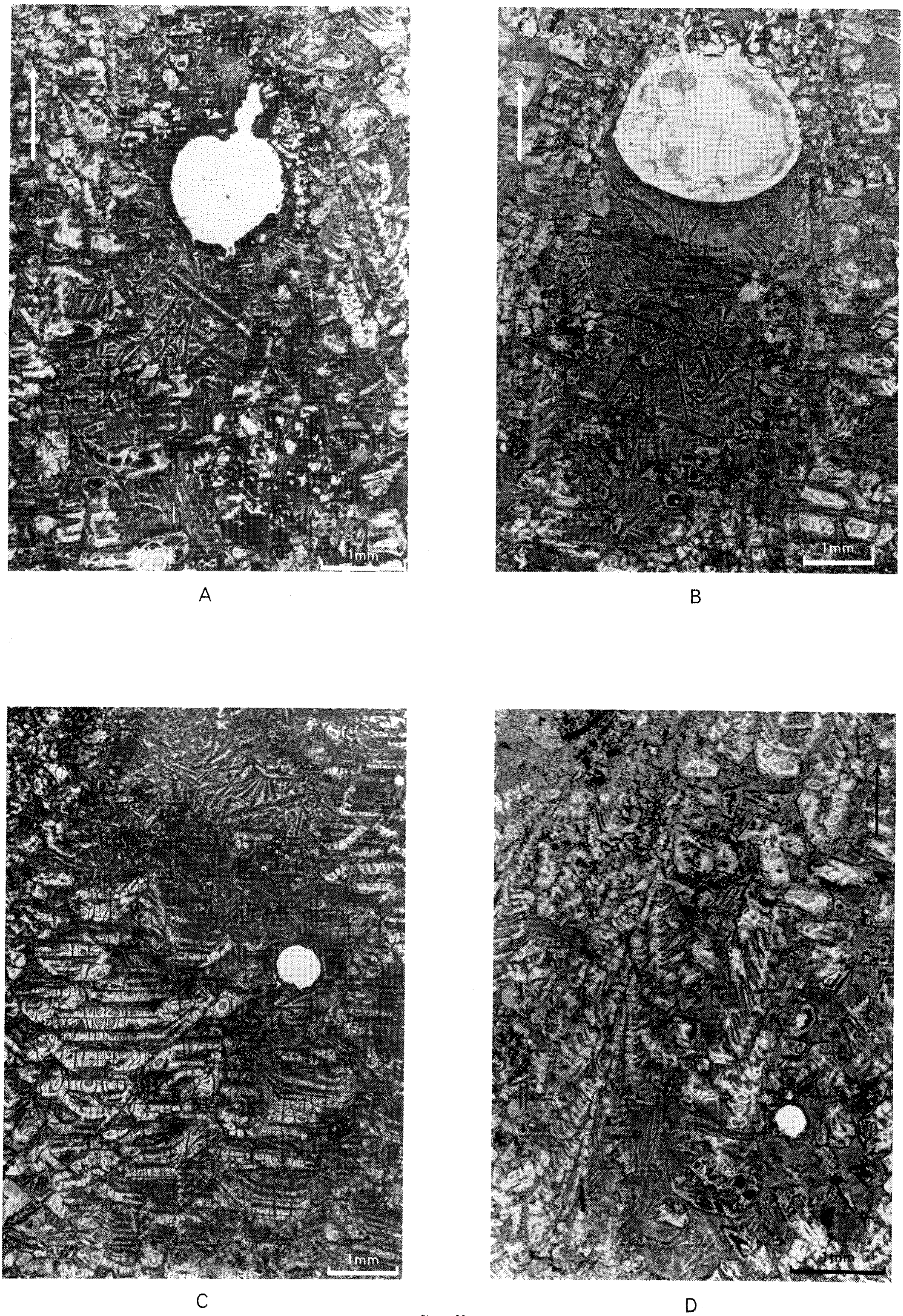

Figure 38

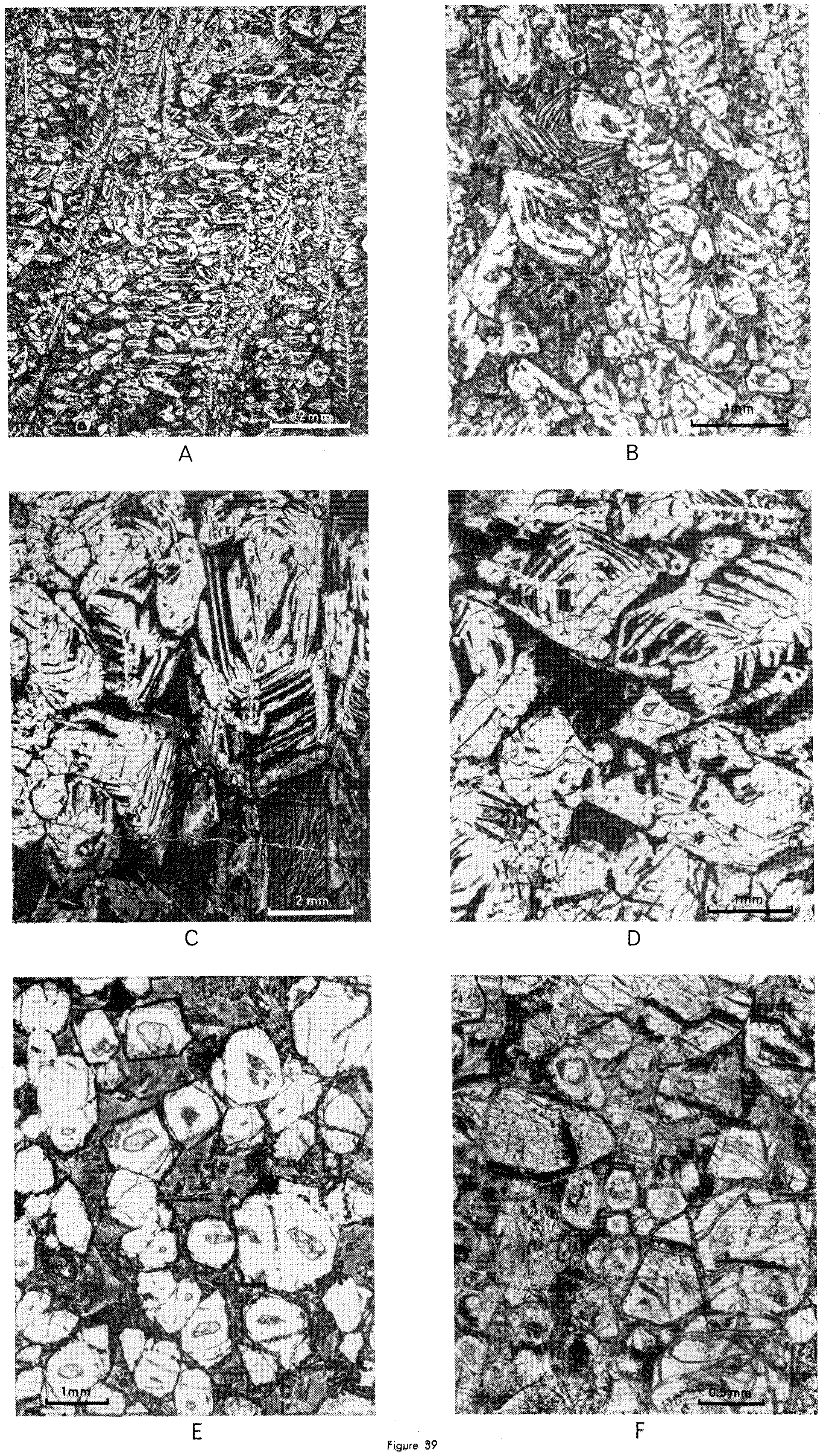

Figure 39

are exceedingly well preserved (Figs. 38 and 39) and allow the flow to be divided into several textural types as follows:

(4) Amygdaloidal peridotite with dendritic olivine crystals

(3) Transitional zone with skeletal olivine

(2) Porphyritic peridotite with equant euhedral olivine phenocrysts

(1) Basal zone of olivine-rich peridotite with equant olivine crystals.

(1) Basal zone

No transition can be seen in the field between this zone and the bulk of the flow but the basal zone probably occupies the lowest 20 to 30 m of the flow. The rock is totally serpentinized but in thin section (18402)* textures are preserved which show that originally it consisted of closely packed equant olivine grains 1 to 2 mm long with 30 per cent matrix consisting of acicular clinopyroxene and glass and a few grains of chromite (Table 15, Column 1 and Fig. 39, F). Secondary magnetite is concentrated into bands, giving the rock a layered appearance which is not shown by the olivine crystals.

A thin section (18401) of the pale green, bleached serpentinite which marks the base of the flow has few textures preserved except the rough outline of some large olivine crystals up to 4 mm long and a few chromite octahedra up to 0.8 mm across. The rock is now largely antigorite with a dusting of secondary opaque oxides and, in addition to the chromite, contains a few small relics of red-brown phlogopite which may also be an original mineral.

TABLE 15. MODAL ANALYSES OF ROCKS FROM MURPHY WELL

	18402	18403	18404	26652
Serpentine	69·9*	45·0 } 55·9	53·1 } 60·6	50·6 } 57·5
Olivine	....	10·9 }	7·5 }	6·9 }
Clinopyroxene	}	21·9	18·9	26·0
Chromite	} 30·1	4·5	4·6	3·2
Glass	}	17·7	15·9	9·1
Amygdales	}	....	....	4·2

* 18402 is totally serpentinized, this figure refers to pseudomorphs after olivine.

(2) Porphyritic Peridotite

This rock type forms the bulk of the flow and with the transition zone to the amygdaloidal flow top is about 120 m thick. The rock is fairly fresh and much of the original mineral assemblage is still present. Textures have been particularly well preserved so that the modal analyses of two specimens (18403, 18404) presented in Table 15 indicate with reasonable accuracy the original composition of the rock. This zone of the flow is an olivine peridotite containing about 60 per cent of euhedral, equant, olivine crystals from 0.5 to 2 mm long with a few larger crystals up to 3 mm long in a matrix of acicular clinopyroxene crystals up to 1 mm long, a pale brown glass and a few euhedral or skeletal chromite crystals up to 1 mm across.

The olivine has been extensively serpentinized but most crystals retain kernels of unaltered olivine. Serpentinization has forced excess iron in the olivine to the margins of the crystal where it now forms a fringe of granular magnetite (see Fig. 39, E and Fig. 40). In modal analyses this fringe was counted with serpentine as it belongs to original olivine.

The remaining 40 per cent of the rock consists of fresh acicular clinopyroxene and a little chromite in a glassy matrix. The pyroxene needles range from small hair-like crystals to more prismatic crystals up to 1 mm long and although some appear to have nucleated on olivine crystals the majority occur randomly throughout the glass. Chromite grains, which make up about 4.5 per cent of the rock, are sometimes euhedral octahedra but more commonly are skeletal crystals. The glass matrix is everywhere devitrified although under low power magnification it commonly appears isotropic. Under high power magnification it is seen to consist of a very fine-grained feathery aggregate of minerals with a very low birefringence, possibly a chlorite, with a fine dusting of exsolved iron oxide.

The overall texture of the peridotite in this zone is porphyritic, with relatively large euhedral olivine crystals set in a fine-grained matrix. Although this texture has been used (eg. Naldrett and Mason, 1968) to suggest that the olivine formed during an early phase of crystallization prior to extrusion it will be argued later that the olivine of the Murphy Well peridotite crystallized after extrusion.

(3) Transition zone

The transition zone cannot be distinguished in the field but from the examination of thin sections is a narrow zone that begins near the top of the porphyritic zone and extends into the lower part of the amygdaloidal flow top. The transition zone is characterized by the development of large (up to 6 mm across), discrete, skeletal olivine crystals which are easily distinguished from the euhedral non-skeletal olivine of the porphyritic zone below but do not take on the complex dendritic habit of the olivine in the overlying amygdaloidal zone. The transition zone is not a distinct zone and Saratovkin (1959) maintains that there is no essential difference between skeletal and dendritic crystals. The physical conditions of this zone, therefore, represent the onset of conditions which lead to the delicate forms to be described in the amygdaloidal zone. The mineralogy and texture of the glass and clinopyroxene fraction is similar to that of the porphyritic zone and only the habit of the olivines is different. The nature of this difference is shown in Figures 39, B, C and D where 18405 is free from amygdales and shows both equant and skeletal forms while in 18421 the skeletal forms have developed into more complex dendritic olivine in a rock which contains a few small amygdales.

(4) Amygdaloidal peridotite

The uppermost 21 m of the flow is well defined in the field by the presence of numerous amygdales which on weathered surfaces of the peridotite appear as small protuberances or pits up to 1 cm across. In thin section, apart from the amygdales, the rock is distinctive because of the dendritic habit of the olivine. Modally the rock is similar to the porphyritic peridotite as shown in Table 15 and the mineralogy and degree of serpentinization is also similar.

Initially the olivine appears to be in the form of small skeletal crystals (Fig. 38, C and 39, A) but examination of the extinction of the olivine remnants reveals optical continuity over areas up to 1 cm across. This shows that the skeletal forms are part of a larger dendritic crystal. These are the largest olivine crystals found in the flow although about 40 per cent of their volume is made up of glass and pyroxene needles either enclosed in the skeletal parts or between the branches of the large dendritic crystal. Individual dendritic crystals appear to be in random orientation and xenomorphic towards each other. A second, less common, type of olivine crystal is plumose in outline (Fig. 38, D and 39, A). Plumose crystals are elongated skeletal olivines up to 5 mm long which

* Thin section numbers refer to G.S.W.A. collection

FIGURE 39 (opposite)

Photomicrographs of the Murphy Well peridotite lava

A 18420 Plumose and dendritic olivine of the amygdaloidal zone.

B 18421 Transition zone : skeletal and dendritic olivine in a peridotite with a few small amygdales.

C 18405 Transition zone : skeletal olivine.

D 18405 Transition zone : skeletal and euhedral olivine crystals.

E 18405 Porphyritic peridotite : note rim of expelled magnetite fringing each serpentinized olivine.

F 18403 Basal zone : serpentinized olivine peridotite.

appear to originate from a point nucleus and grow wider as they grow away from the nucleus, resulting in an ostrich plume appearance for the crystal. Unlike dendritic olivine the plumose crystals have a constant orientation with the specimen and are a facing structure with the nucleus uppermost.

Amygdales are numerous in the rock but usually quite small, from 1 mm to 3 mm being the common size although rare examples up to 1 cm across may be found. The amygdales are usually spherical to subspherical but often show irregular extensions (Fig. 38, B). The amygdales contain a variety of minerals, principally a very fine-grained colourless or pale green, nearly isotropic, chloritic material and a little calcite, but often with a few small octahedra of magnetite and sheaves of tremolite. The minerals are sometimes arranged irregularly within the amygdale but are usually in a zonal arrangement with a rim of magnetite grains along the amygdale margin. A further feature of the amygdales is that they have a "tail" of pyroxene-rich material several times the size of the amygdale (Fig. 38, A and B) which consists of acicular clinopyroxene and glass without any olivine. Opposite the tail, where the amygdale is in contact with the olivine-rich peridotite, the serpentinization of the olivine is always complete and the serpentine is particularly strongly dusted with magnetite. The tails of the amygdales are aligned with one another and give a further facing texture with the tail pointing downward. This is shown in Figure 38, A where a poor example of plumose olivine occurs a little to the right of the amygdale. The pyroxene-rich tail and the iron-rich halo of the amygdales are responsible for the bumps and pits on the weathered rock, the halo is resistant to weathering and forms a bump on the upper surface of a specimen while the tail, and the amygdale contents, are less resistant and form pits on the undersurface.

CHEMISTRY

The chemical characteristics of the Murphy Well rocks are presented in Tables 16 and 17, with analyses of comparable rock from other localities in Table 18. Electron probe analyses of mineral phases and interstitial glass from the Murphy Well ultramafite are given in Table 19.

TABLE 16. ANALYSES OF THE PERIDOTITE LAVA FROM MURPHY WELL

Sample No.	1	2	3	4	5	6	7	8	9	10
	18401	18402	18403	18404	18405	18406	18407	18408	18409	26652
SiO_2	41·0	39·7	40·2	39·8	40·8	40·5	40·4	40·3	40·4	40·56
Al_2O_3	2·5	2·2	4·2	4·5	5·0	4·4	4·9	5·0	4·7	4·58
Fe_2O_3	5·1	9·1	4·7	4·8	5·8	5·2	5·7	5·7	6·4	5·05
FeO	1·03	0·64	4·07	4·01	4·23	4·21	4·04	4·03	3·27	4·34
MgO	34·5	33·2	32·3	31·7	30·0	32·1	30·4	29·2	31·3	31·50
CaO	0·24	0·11	3·85	3·98	4·26	4·33	4·37	4·82	4·11	3·65
Na_2O	....	....	0·05	0·10	0·25	0·17	0·20	0·05	....	0·08
K_2O	....	....	....	....	0·10	....	....	....	....	0·12
H_2O^+	12·84	11·73	8·99	9·30	9·39	8·55	9·12	8·78	9·60	8·71
H_2O^-	1·41	2·27	0·15	0·13	0·36	0·30	0·35	0·34	0·60	0·49
CO_2	0·10	....	....	0·26	....	0·18	....	0·10	0·14	0·21
TiO_2	0·11	0·10	0·19	0·21	0·23	0·21	0·23	0·24	0·22	0·24
P_2O_5	....	....	0·02	0·20	0·05	0·30	0·03	0·01	0·03	0·04
MnO	0·09	0·16	0·17	0·16	0·17	0·18	0·18	0·18	0·18	0·14
Total....	98·9	99·1	98·9	99·0	100·6	100·5	99·9	98·8	100·9	99·71
Trace Elements (ppm)										
Co	120	160	130	130	120	120	120	120	130	260
Cr	1630	1560	1730	1670	1800	1690	1680	1670	1680	1642
Cu	100	35	55	40	55	45	60	60	45	200
Ni	2900	2800	1900	1900	1700	1900	1700	1700	1900	2100
S	420	310	260	260	280	280	280	320	180	400
V	50	70	110	120	120	110	120	120	90	190

Analysts : Govt. Chemical Laboratories, 1–9 : N. Marsh by X. R. F. except FeO, alkalis, CO_2 and H_2O 10 : J. R. Gamble (chemical methods). Trace elements : atomic absorption. 1,2 : Totally serpentinized olivine peridotite of basal zone ; 3,4 : ' Porphyritic ' peridotite ; 5,6 : Peridotite of transition zone: 7–10 : Amygdaloidal peridotite.

TABLE 17. ANALYSES OF MURPHY WELL LAVA RECALCULATED ANHYDROUS

	1	2	3	4	5	6	7	8	9	10
SiO_2	47·9	46·2	44·2	44·1	45·2	44·5	44·6	44·4	45·1	44·8
Al_2O_3	2·9	2·6	4·6	5·0	5·5	4·8	5·4	5·5	5·2	5·1
Fe_2O_3	2·0	2·0	2·0	2·0	2·0	2·0	2·0	2·0	2·0	2·0
FeO	4·75	8·46	7·33	7·42	8·68	7·97	8·33	8·28	8·28	7·80
MgO	40·3	38·6	35·5	35·1	33·2	35·3	33·6	32·2	34·9	34·8
CaO	0·28	0·30	4·24	4·41	4·72	4·76	4·83	5·31	4·58	4·03
Na_2O	....	....	0·05	0·11	0·28	0·18	0·22	0·05	....	0·09
K_2O	....	....	....	....	0·10	....	....	....	....	0·10
TiO_2	0·13	0·11	0·21	0·23	0·25	0·23	0·25	0·26	0·24	0·26
P_2O_5	....	....	0·02	0·02	0·05	0·03	0·03	0·01	0·03	0·04
MnO	0·10	0·19	0·19	0·18	0·19	0·20	0·20	0·20	0·20	0·15
C.I.P.W. Norm										
Q	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
C	2·39	2·05	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
Or	0·00	0·00	0·00	0·00	0·59	0·00	0·00	0·00	0·00	0·59
Ab	0·00	0·00	0·42	0·93	2·37	1·52	1·86	0·42	0·00	0·76
An	1·39	1·49	12·33	13·15	13·46	12·29	13·75	14·78	14·19	13·22
Di	0·00	0·00	6·77	6·78	7·63	8·79	7·92	9·10	6·59	5·14
Wo	0·00	0·00	3·58	3·59	4·02	4·65	4·18	4·80	3·48	2·72
En	0·00	0·00	2·81	2·81	3·07	3·61	3·22	3·68	2·69	2·12
Fs	0·00	0·00	0·38	0·38	0·53	0·53	0·52	0·62	0·42	0·31
Hy	53·19	46·86	22·91	21·07	21·74	18·20	20·75	23·99	24·80	25·12
En	49·70	40·88	20·21	18·54	18·55	15·86	17·85	20·54	21·46	21·95
Fs	3·49	5·98	2·70	2·53	3·19	2·34	2·90	3·46	3·34	3·17
Ol	38·24	44·95	52·57	53·26	50·90	55·76	51·74	46·50	51·52	50·85
Fo	35·50	38·72	45·82	46·29	42·79	47·96	43·88	39·23	43·98	43·86
Fa	2·74	6·24	6·75	6·96	8·11	7·80	7·86	7·27	7·54	6·98
Mt	2·90	2·90	2·90	2·90	2·90	2·90	2·90	2·90	2·90	2·90
Il	0·25	0·21	0·40	0·44	0·47	0·44	0·47	0·49	0·46	0·49
Ap	0·00	0·00	0·05	0·05	0·12	0·07	0·07	0·02	0·07	0·09

NOTE : Sample numbers as for Table 16. Fe_2O_3 has been reduced arbitrarily to 2 per cent, for explanation see text.

The most striking feature of the analyses is the uniformity of rocks from the porphyritic, transitional and amygdaloidal zones of the flow. Within the limits of the analytical method it would appear that the rocks cystallized from a magma of uniform composition. The high degree of serpentinization makes interpretation of analyses of the basal zone of the flow difficult. Two analyses (Table 16, Columns 1, 2) are given and the degree of serpentinization is indicated by the high H_2O^+ values. The preservation of original textures in 18402, as in other rocks from this area, indicates that serpentinization was a constant volume process but the presence of plentiful pseudomorphs of pyroxene suggests that the rock contained much more CaO than the 0.11 per cent measured. Thayer (1966) argues that MgO, CaO, FeO and SiO_2 are expelled during constant volume serpentinization but the analyses would suggest that only CaO and Al_2O_3 have suffered any marked loss and that FeO has been oxidized to Fe_2O_3 but remained within the system. These data partially support Page (1967) who argues that CaO is removed in greater proportion than MgO. Serpentinization makes interpretation of these analyses difficult and recalculation on an anhydrous basis, as presented in Table 17, is strictly speaking not valid as an indicator of the original composition of the rock.

The chemical characteristics of the less altered bulk of the Murphy Well flow (Table 16, Columns 3-10) are similar to rocks from Marshall Pool and Scotia in Western Australia and Dundonald in Canada (Table 18, Columns 1, 2, 4, 6, 7) in having a higher calcium and aluminium content than the average peridotite (Table 18, Column 13) but lower than that of typical picrites. Unlike the peridotitic "komatiites" of Viljoen and Viljoen (1969a) (Table 18, Columns 8-10 this paper) the alumina content is high and the CaO/Al_2O_3 ratio is consistently less than unity, ranging from 0.8 to 0.99. Similarly the variation of these elements within a body, from low values at the base to higher values at the top, together with the variation in modal minerals, is used by Viljoen and Viljoen (1969a) and Nesbitt (1971) to demonstrate differentiation and the concentration of a pyroxene-rich liquid towards the top of the flow. At Murphy Well the concentration of calcium and aluminium is sensibly constant throughout the major part of the flow and is in conformity with the modal analyses (Table 15) which indicate a lack of differentiation. The closest comparison between the Murphy Well lava and peridotites at Scotia and in South Africa appears to be with the central portions of the bodies; in other words it corresponds with the average peridotite at these localities and has crytallized without differentiation.

TABLE 18. REPRESENTATIVE ANALYSES OF PERIDOTITES AND PICRITES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	40·08	41·42	43·70	42·10	38·40	41·20	41·00	40·36	42·06	41·58	40·02	43·00	43·54	44·82
Al_2O_3	4·70	5·33	6·10	4·35	2·80	4·90	4·90	1·97	2·21	3·44	4·39	4·64	3·99	10·29
Fe_2O_3	5·19	4·79	2·94	4·45	4·83	} 12·10	10·70	{ 5·84	4·73	5·20	3·50	2·42	2·51	1·88
FeO	4·22	4·27	5·27	5·69	3·17			{ 3·75	5·23	6·01	3·81	6·47	9·84	8·93
MgO	30·50	29·70	27·85	30·77	38·78	28·00	28·50	35·17	29·93	26·71	33·82	33·45	34·02	22·07
CaO	4·16	4·89	6·25	3·74	1·52	4·50	2·80	3·45	5·18	5·99	2·75	3·99	3·46	8·06
Na_2O	0·12	0·16	0·19	0·17	0·10	....	....	0·05	0·16	0·12	0·21	0·25	0·56	0·94
K_2O	0·10	0·07	0·02	0·03	0·06	....	....	0·00	0·02	0·03	0·05	0·05	0·25	0·10
H_2O^+	7·66	7·77	} 6·92	8·48	10·10	8·42	12·74	{ 7·76	8·62	9·03	10·10	3·83	0·76	1·41
H_2O^-	0·31	0·17						{ 0·21	0·15	0·18	0·51	1·22	....	0·92
TiO_2	0·29	0·31	0·28	0·18	0·14	0·29	0·32	0·41	0·31	0·38	0·20	0·18	0·81	0·78
P_2O_5	....	....	....	....	....	....	....	....	0·02	....	0·00	0·00	0·05	0·12
Cr_2O_3	0·40	0·40	....	....	....	0·58	0·31	....	0·31	0·30	0·32	0·51	....	....
MnO	0·10	0·11	0·20	0·20	0·15	0·15	0·10	....	0·16	0·19	0·08	0·15	0·21	0·11
NiO	0·30	0·30	....	....	....	0·17	0·29	0·25	0·18	0·15	....	0·00	....	....
Total	98·13	99·79	99·72	100·16	100·05	100·34	100·69	99·63	99·76	99·70	99·88	99·68	100·00	100·08

1. Vesicular peridotite, Marshall Pool, W.A. (McCall and Leishman, 1971)
2. Peridotite, Marshall Pool, W.A. (McCall and Leishman, 1971)
3. Plate spinifex peridotite, Scotia, W.A. (Nesbitt, 1971)
4. Olivine peridotite, Scotia, W.A. (Nesbitt, 1971)
5. Harrisitic olivine peridotite, Scotia, W.A. (Nesbitt, 1971)
6. Peridotite (SA37), Dundonald, Ontario (Naldrett and Mason, 1968)
7. Peridotite (SA412), Dundonald, Ontario (Naldrett and Mason, 1968)
8. VU32A, olivine peridotite, base of flow, Barberton, South Africa (Viljoen and Viljoen, 1969a)
9. V2, peridotite, centre of flow, Barberton, South Africa (Viljoen and Viljoen, 1969a)
10. AU5, pillowed peridotite, top of flow, Barberton, South Africa (Viljoen and Viljoen, 1969a)
11. Serpentinized peridotite, Lizard, Cornwall, U.K. (Green, 1964)
12. Vitrophyric peridotite, pillow lava, Cyprus (Gass, 1958)
13. Average peridotite (23 analyses) (Nockolds, 1954)
14. Picrite sheet, Ubekendt Ejland, Greenland (total includes 0·15 per cent CO_2) (Drever, 1956)

TABLE 19. ELECTRON PROBE ANALYSES OF MINERAL PHASES (AVERAGE OF TWO SPOT ANALYSES)

	18403			13404			26652		
	Ol	Cpx	Glass	Ol	Cpx	Glass	Ol	Cpx	Glass
SiO_2	41·2	47·5	35·5	39·3	46·4	35·8	40·0	48·4	35·5
Al_2O_3	0·1	6·5	10·1	0·2	6·6	9·1	0·0	5·1	9·1
FeO	6·5	7·3	4·6	6·6	6·8	5·0	8·6	8·3	4·0
MgO	53·3	13·1	33·3	49·9	13·4	33·2	47·8	14·7	31·1
CaO	0·0	22·4	1·1	0·0	22·0	1·6	0·0	18·7	0·8
NiO	0·42	0·02	0·14	0·20	0·0	0·12	0·49	n.d.	0·10
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·67	n.d.
Total	101·52	97·02	84·74	96·20	95·2	84·82	96·89	95·87	80·60
Si	0·97	1·80		0·99	1·86		1·01	1·93	
Al′	....	0·20		....	0·14		....	0·07	
Al	....	0·09 }		....	0·02 }		....	0·05 }	
Fe	0·13 } 2·03	0·24 } 2·00		0·14 } 2·01	0·23 } 2·00		0·18 } 1·99	0·28 } 2·00	
Mg	1·90 }	0·77 }		1·87 }	0·80 }		1·81 }	0·87 }	
Ca	....	0·90 }		....	0·95 }		....	0·80 }	

Atomic Ratios

Mg	93·1	39·6		92·8	40·8		90·5	44·8	
Fe	6·9	12·2		7·2	11·5		9·5	14·2	
Ca	....	48·2		....	47·7		....	41·0	

Outside the major Archaean terrains comparable analyses have been obtained for the high-temperature peridotite of the Lizard area, Cornwall, U.K., intruded during the Hercynian Orogeny (Green, 1954) and the possibly Triassic ultrabasic pillow lavas of Cyprus (Gass, 1958). Representative analyses of these rocks are included in Table 18.

Table 17 gives the analyses of the Murphy Well ultramafite recalculated anhydrous and with all except 2 per cent of the Fe_2O_3 recalculated to FeO. The justification for this is that much of the ferric oxide present is due to the post-crystallization serpentinization of the olivine and adversely affects the olivine/pyroxene ratio of the norm. The resulting analysis is thought to represent fairly reliably the original magma as it would appear from the textures and that part of the original mineralogy preserved that chemical losses from the system due to serpentinization are only minor. Iron expelled from serpentinized olivine is concentrated along the margin of the crystal as partially oxidized magnetite and the original interstitial glass is devitrified rather than recrystallized. Both factors indicate that the movement of ions has been of local significance only and this is supported by the electron probe analyses of the glass (Table 19) and the electron probe scan across a relict olivine grain in Figure 40. These criteria do not apply to the analyses of the basal peridotite which is totally serpentinized and has lost most of its calcium and probably some iron and aluminium as well.

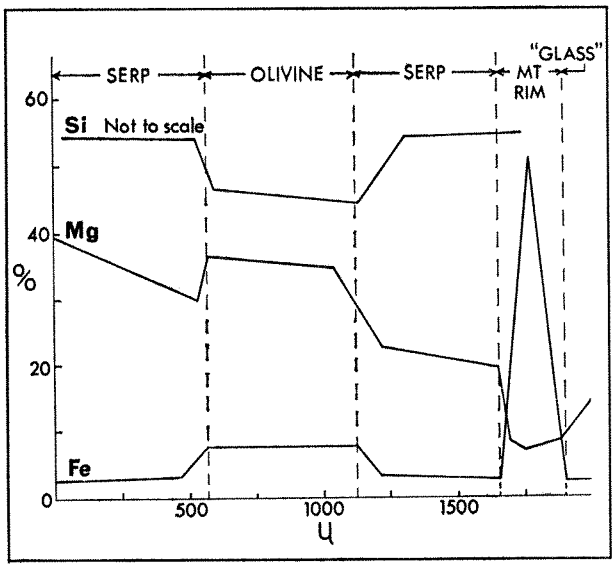

Figure 40. Electron probe scan across relict olivine grain in 26652 (analyst : J. Hallberg, C.S.I.R.O.).

If analyses 3 to 10 of Table 17 represent the original magma then the rock normatively was an ultrabasic olivine-rich peridotite with almost twice as much olivine as pyroxene. The pyroxene of the norm is predominantly orthopyroxene, a feature noted from the norms of both Canadian and South African examples. While some orthopyroxene was noted in the overlying lenses of ultramafics at Dundonald township, Ontario (Naldrett and Mason, 1968) none is seen in the rocks from Murphy Well or the ultramafic lavas from Munro township, Ontario (Pyke and others, in press). This is accounted for by the highly aluminous nature of the modal clinopyroxene which results in the calcium being used to convert hypersthene to augite rather than forming anorthite (Pyke and others, in press). Similarly the normative plagioclase present varies from 13 to 16 per cent while none is observed in the mode, in fact the calcium and aluminium are present as clinopyroxene rather than anorthite.

Electron probe data in the mineral phases present in the Murphy Well peridotite are presented in Table 19. Olivine, pyroxene and devitrified glass were probed in each of three specimens where preservation was considered good. The olivine is highly magnesian and varies from $Fo_{90\cdot5}$ to $Fo_{93.1}$. This is more forsteritic than the usual olivine from basic rocks and most peridotites but is the range commonly found in Archaean peridotites, although in the overlying lenses at Dundonald the olivine ranges only from Fo_{85-90} (Naldrett and Mason, 1968). Although there is an apparent rise in the fayalite content of the olivine towards the top of the Murphy Well flow insufficient data are available to determine whether this is other than experimental variation, or, perhaps, zoning within the olivine crystals (see Pyke and others, in press). The clinopyroxene of the Murphy Well ultramafite is high in both calcium and aluminium and is diopsidic. The iron content of the pyroxene in 18403 and 18404 brings it into the salite field of Poldervaart and Hess (1951) while a decrease in the calcium brings 26652 into the augite field. High alumina clinopyroxenes are becoming a commonly recognized feature of Archean peridotites (Nesbitt, 1971; Pyke and others, in press) and owing to the mode of emplacement of these bodies cannot be considered a feature of high-pressure crystallization as suggested by Green (in Wyllie, 1967).

The significance of the analyses of devitrified glass from the Murphy Well ultramafite is problematical. The glass is rich in alumina and magnesia but poor in silicon and calcium. The analyses, despite their internal agreement, never total more than 85 per cent and it is possible that the remainder is largely H_2O^+. Serpentinization of adjacent olivine has possibly distorted the analyses from the original composition of the glass. Figure 38 suggests that magnesia is released from the olivine by serpentinization and silica is increased, possibly by extraction from the glass. Aluminium and calcium however are not involved in the process of serpentinization and are possibly near their original levels. The present mineralogy of the devitrified glass is possibly a highly magnesian chlorite. The overall composition of the glass, even with allowance for transfer of ions does not suggest a particularly silica-enriched residual fraction and is richer in magnesium and poorer in calcium than those reported by Nesbitt (1971).

DISCUSSION

ULTRAMAFIC MAGMAS

The possibility of a true ultrabasic magma was dismissed by Bowen (1928, p. 166) both on theoretical grounds due to the very high temperatures required to produce a peridotite liquid and on the practical grounds that no ultrabasic rocks were known that were aphanitic or had a glassy ground mass. Instead Bowen proposed that all ultrabasic rocks were formed by the intrusion of a crystal mush consisting of cumulate olivine crystals and a small proportion of basaltic liquid to act as a "lubricant". Bailey and McCallien (1953), to reconcile certain field evidence from serpentinite bodies near Ankara, Turkey, proposed the existence of a serpentine magma which could be extruded as lava flows. More recently Taylor (in Wyllie, 1967) has proposed the intrusion of an ultrabasic magma to explain certain complexes of Cretaceous or Tertiary age in southeast Alaska. The conflict between the experimental and the field evidence—the "Magnificant Argument" has been reviewed by Wyllie (1967) but at the time the evidence of Archaean ultramafic bodies like the Murphy Well peridotite was not available. Viljoen and Viljoen (1969a) have also reviewed recent experimental data and have reconciled it with their evidence of estrusive peridotites in the Barberton region of South Africa.

Recognition that the spinifex texture found at the margins of many Archaean peridotites represents a quench texture and the presence of devitrified glass in these peridotites (Naldrett and Mason, 1963; Viljoen and Viljoen, 1969a; Lewis, 1971; Nesbitt, 1971) removes the practical objections that Bowen had to an ultrabasic magma.

In comparison with other ultramafic flows the Murphy Well ultramafite shows both similarities and differences. The chemical characteristics of the flow have been commented on earlier and the textural similarity of the porphyritic zone to the central zones in other Achaean ultramafites is well marked. Differences include the thickness of the unit which is greatly in excess of that reported from the ultramafic flows in South Africa (Viljoen and Viljoen, 1969a), Canada (Pyke and others, in press) and near Mount Clifford, W.A. (Barnes, 1972, pers. comm.), the preservation of an amygdaloidal flow top which has not been reported before, although certain rocks at Marshall Pool appear to be similar (McCall and Leishman, 1971), the dendritic nature of the olivine in the flow top and the apparent lack of differentiation within the body.

In all other reports ultramafic flows are thin, from 12 m to 30 m in the Barberton Mountain land, South Africa, from 1 m to 17 m in Munro township, Canada and from 5 m to 15 m at Mount Clifford, W.A. The Murphy Well lava has a thickness of 162 m and although poor exposure may conceal flow divisions within the body no indication of this was found either in the field or in petrographic studies.

The nature of the magma envisaged by most authors for ultramafic flows and near surface sills is similar. A magma is proposed with a liquid fraction, capable of crystallizing a pyroxene peridotite, in which olivine crystals are suspended. Viljoen and Viljoen (1969a, p. 98) draw attention to the small effect that gravitative settling will have on small olivine crystals in a rapidly crystallizing mass and all authors invoke the flow differentiation described by Bhatacharji (in Wyllie, 1967) to account for the quench crystallization of a nuclei-free upper spinifex layer containing about 40 per cent olivine and lower layers containing up to 80 per cent euhedral olivine crystals. In the Murphy Well ultramafite, however, modal analyses (Table 15) show a constant 60 per cent olivine throughout the bulk of the unit only rising to 70 per cent in the basal few metres. Chemical analyses (Table 16) also indicate a lack of differentiation. In addition, even in those flows where differentiation is demonstrable a proportion of the euhedral olivine must have crystallized directly from the interstitial liquid after extrusion.

The crystallization of olivine under conditions of rapid cooling have been studied by Drever and Johnston (1957) and their work on skeletal olivine has been extended by Lewis (1971) and Nesbitt (1971) to demonstrate that spinifex texture is the result of quenching of a nuclei-free ultrabasic liquid. Lewis (1971) observed that no analogue of the dendritic fayalite seen in slags had been encountered in nature but the Murphy Well lava does contain similar dendritic crystals in the amygdaloidal flow top. That these delicate crystals formed directly from a quenched liquid cannot be doubted but why in this instance small scale dendritic crystals should form throughout a thickness of 21 m rather than large plates of spinifex textured olivine is not clear. Possible explanations include the presence of amygdales, the surface of which could have generated sufficient nuclei to crystallize the liquid simultaneously throughout the thickness of the flow top or the lack of any flow differentiation which could have cleared nuclei from this portion of the flow. Although nuclei were obviously plentiful no porphyritic olivines are observed in the flow top. It is not necessary, with the Murphy Well peridotite, to postulate superheating of the liquid to remove nuclei as proposed by Nesbitt (1971) in his discussion of the formation of spinifex texture. A further difference between the dendritic texture of the Murphy Well peridotite and spinifex texture is its non-directional nature. Spinifex texture is directional with the long axes of the olivine plates perpendicular to the cooling surface whereas the dendritic olivines of the Murphy Well rocks have crystallized from a multitude of internal nuclei and are randomly oriented. Directional crystallization is observed at Murphy Well but the plumose olivines are very subordinate to the dendritic.

The uniformity of chemical composition of the Murphy Well ultramafite and the undoubted liquid nature of the amygdaloidal flow top leads to the question of the origin of the euhedral olivine crystals of the bulk of the flow. Any form of differentiation is ruled out and the rise of gas bubbles would have the effect of homogenizing the magma after extrusion. We are drawn to the conclusion, therefore, that the magma of the central portions of the flow was similar to that at the top, i.e. a liquid with no phenocrysts but with many submicroscopic nuclei. Most authors have considered the euhedral olivine to be phenocrysts and present at the time the magma was extruded. This view is stated clearly by Naldrett and Mason (1968, p. 124) who ". . . suggest that the mineral was crystallized in two very different environments. The equant grains are characteristic of olivine cumulates the world over . . . (and) . . . crystallized under normal conditions of relatively slow cooling". Unless it is suggested that the liquid portion was itself differentiated we must conclude that the Murphy Well magma was extruded as a crystal-free liquid and that the crystal habit of olivine is extremely sensitive to very small variations in physical conditions and rate of cooling at the point of crystallization. This is essentially the conclusion reached by Drever and Johnston (1957, p. 310).

TEMPERATURE OF EXTRUSION OF ULTRAMAFIC LAVAS

No direct observations have been made on the temperature of extrusion of ultramafic lavas but Viljoen and Viljoen (1969a) after an examination of recent experimental work suggest a temperature of about 1,400°C, not too far above the known temperatures of basaltic magmas. Häkli and Wright (1967) have demonstrated that the fractionation of nickel between augite and olivine is a reliable geothermometer for Hawaiian olivine basalts and it is possible that this method could give a direct value of the crystallization temperature of ultramafic rocks in which the original mineralogy is preserved. The data presented in Table 19 are insufficient and use of the graphs of Häkli and Wright gives no consistent figure but the lowest value obtained is approximately 1,400°C using the olivine/pyroxene ratio from 18403 and the authors suggest this might be a method worth further investigation.

AMYGDALES

The amygdales in the upper 21 m of the Murphy Well lava provide an exceptional point of interest due to their excellent state of preservation (Fig. 38, A and B). Their general characteristics have been described above and they will be reconsidered here for the evidence they give on the crystallization of the magma. Similar poorly preserved amygdales have been described from Marshall Pool, W.A. (McCall and Leishman, 1971) but from pyroxene-rich peridotites.

The authors interpret the tail of pyroxene-rich material as being residual liquid that flowed into the path cleared by the rising gas bubble through a forest of rapidly growing dendritic olivine crystals. No obvious tail could form until the olivine crystals were sufficiently well developed not to move in behind the rising bubble and the whole process stopped when the olivine dendrites were sufficiently well formed to physically hold back the bubble. This whole stage took place very rapidly as the longest tail is only about three times the bubble diameter, and small bubbles have poorly developed tails. That the residual liquid at this stage was very fluid is shown not only by the presence of a pyroxene-rich tail but by the flame structures developed at the top of many amygdales which are interpreted as the escape upward of smaller bubbles after the larger bubble had been trapped. This interpretation is supported by the amygdale figured in Figure 38, B which is seen to have two radii of curvature with a narrow arc of magnetite octahedra within the pyroxene tail which continues the upper surface of the amygdale. It is suggested that a short while after the amygdale had been arrested by the olivine dendrites it was able to partially escape upward and as more residual liquid filled the space behind it left the arc of magnetite as an indicator of its former position. Following this reasoning the halo of complete serpentinization that surrounds each amygdale is thought to be due to the post-crystalization escape of the amygdale fluids into the surrounding peridotite.

If this interpretation of the amygdales is accepted then it will be seen that the olivine in the rock crystallized from a low viscosity liquid although the devitrification of glass can produce textures with a large degree of similarity (Rodgers, 1970).

Although vesicles from ultramafic rocks have not been studied before, Smith (1967) has studied segregation vesicles in basalt which show certain similarities. Smith interprets these vesicles as having contracted during cooling with the resultant entry of interstitial residual liquid into the vesicle. In this way the principal surface of the vesicle remains ellipsoidal but the remaining vesicle is highly irregular in shape, is entirely surrounded by glass and is often split into several smaller irregular vesicles. This interpretation is not possible for the amygdales of the Murphy Well peridotite as they are usually spherical in shape, show no change of shape due to intruding liquid and on the contrary often show apophyses which indicate an excess pressure in the amygdale rather than insufficient pressure to maintain its shape. Upton and Wadsworth (1971) use Smith's mechanism to explain rhyodacite tails to vesicles in a basalt from Reunion. It is noted that the tails are directional and that the spherical gas bubble occupies the upper part of the vesicle. From the published illustrations (Upton and Wadsworth, 1971, Figs. 1 and 3) it would appear that the tails formed during the upward passage of the vesicle in a manner similar to that described for the Murphy Well ultramafite rather than by infilling of a larger vesicle.

SERPENTINIZATION

As seen in Table 15, the Murphy Well rocks, except for the basal layer, are partially serpentinized periodotites containing 45 to 53 per cent serpentine. The serpentine is all formed by the partial replacement of olivine. Thayer (1966) has argued that serpentinization is a constant volume process that involves significant losses of certain elements, while Viljoen and Viljoen (1969b) have shown that at low levels of serpentinization (H_2O^+ content of rock less than 10 per cent) there is little change in the chemistry of the rock. The preservation of original textures in such perfect detail in the Murphy Well rocks certainly agrees with Thayer's main thesis but it has been shown already that the elements displaced by serpentinization do not leave the system but are located either as a magnetite rim to the pseudomorph or in the devitrified glass. The origin of the water necessary for serpentinization must also be considered. It is generally accepted (Wyllie, 1967) that a peridotitic melt would contain little water and Martin (1971) suggests that serpentine is unstable above 200°C except at very high water vapour pressures. The serpentinization of a surface flow, therefore, is possibly a weathering feature but this would be accompanied by considerable expansion. The amygdaloidal nature of the Murphy Well ultramafite, however, indicates that the magma must have been supersaturated in volatiles which separated very rapidly under low pressure conditions. It is possible that under these circumstances the melt cooled sufficiently rapidly to trap much of the volatile component in the glassy matrix. Serpentinization is then possible by a transfer at low temperatures of components within the rock, so obviating problems of volume change or element loss.

ACKNOWLEDGMENTS

The authors wish to acknowledge helpful discussion with Dr. D. R. Hudson and Dr. J. A. Hallberg and assistance with electron probe analysis by Mr. R. B. W. Vigers, all of C.S.I.R.O. Mineralogical Laboratories, Perth.

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A GUIDE TO THE GEOCHEMISTRY OF NICKELIFEROUS GOSSANS AND RELATED ROCKS FROM THE EASTERN GOLDFIELDS

by R. H. A. Cochrane

ABSTRACT

A reconnaisance survey of gossans developed on areas of nickel sulphide mineralization was carried out during a geochemical orientation investigation in the Eastern Goldfields. One hundred and sixteen samples were collected from 23 localities including all the productive nickel mines. These samples were then analysed by Atomic Absorption Spectroscopy (A.A.S.) for copper, lead, zinc, nickel, cobalt, chromium, manganese, silver, molybdenum and iron.

The range of analytical results obtained from a typical unlateritized gossan derived from nickel sulphide mineralization are:

Cu	Pb	Zn	Ni	Co	Cr	Mn	Ag	Mo	Fe
500	less	less	1000	less	less	less	less	less	10%
to	than	than	to	than	than	than	than	than	to
5000	50	100	5000	1000	500	500	5	5	30%

All results expressed in parts per million (ppm) except for iron (Fe) which is shown as a percentage.

INTRODUCTION

During a geochemical orientation survey of the Eastern Goldfields in May 1972, most known locations of nickel sulphide mineralization were visited. This orientation survey was carried out to provide the necessary background information to determine the criteria for the existence of mineralized cells within the ultramafic rocks of the Leonora and Laverton 1 : 250,000 sheets, and whether these cells could be distinguished on a regional geochemical mapping scale. As gossans were present at many of these locations they were sampled and the results are presented here.

PHYSICAL BACKGROUND

PREVIOUS WORK

Little published work is available on the geochemistry of nickeliferous gossans in Western Australia. A recent paper by Mazzuchelli (1972) describes the geochemical environment of the Kambalda nickel deposit with particular respect to the soil geochemistry and its relation to bedrock and to the underlying ore deposits. A general description of the problem of the interpretation of leached outcrops is given by Blanchard (1968). His work is mostly related to copper, lead and zinc gossans from the eastern States of Australia and from North America, with no reference to nickel.

A great interest in nickel gossans was developed during the "nickel boom" of 1968-1970 in Western Australia. Consequently a large number of companies carried out many studies parallel to this one but as yet none of these results have been published.

LOCATION

The geographical location of samples range from Pioneer Siding in the south (40 km north of Norseman), north to Mount Keith (80 km south of Wiluna) with easterly and westerly sample limits at Mount Windarra (24 km west of Laverton) and Nepean (25 km south of Coolgardie) respectively. The locations are shown in Figure 41.

METHOD OF COLLECTION

All samples were collected by the writer and where possible involved collection in situ, on the surface, in costeans, shafts, winzes etc., when the outcrop still existed. Other samples were collected from larger display specimens "salvaged" by company geologists prior to mine development, or in some cases collection from company archives when the outcrop no longer existed. Where possible at least 250 g of each sample were collected.

All samples carry a G.S.W.A. number e.g. 35001, and refer to an individual specimen. Samples numbered e.g. 35737/A, 35737/B refer to pieces off the original sample 35737 and have been analysed separately.

DEFINITION OF TERMS AND DESCRIPTIONS OF PHYSICAL CHARACTERISTICS

To avoid repetition of terms the following definitions apply:

GOSSAN

A gossan is a moderately heavy accumulation of limonitic material, derived in the main from economic sulphide mineralization or from its iron-yielding gangue associates, which have been leached more or less in place, and normally overlie a mineralized zone beneath.

This definition includes the term *capping* as no distinction is made between material derived from massive and disseminated sulphides. A rock is not normally considered gossanous unless the limonite developed is appreciably porous or cellular and a substantial proportion of the limonite-yielding materials have been leached.

Nickel or nickeliferous gossan refers to gossanous material derived in the main from nickel sulphide mineralization.

Copper gossan means similar material derived in the main from copper sulphides.

False gossan. A false gossan is a moderately heavy accumulation of limonitic material derived from any source, other than economic mineralization, that exhibits the physical properties normally found in a gossan (sensu stricto). It includes gossanous material derived from non-economic sulphide mineralization, typically pyrite.

Laterite. A laterite is an accumulation of oxides of iron, aluminium and other related elements, developed in the arid environment as a resistate mineral assemblage during weathering. Lateritic material is characteristically more dense than gossanous material and is often magnetic.

It is not always practicable to apply exactly these rigorous definitions as most gossans are partially lateritized or silicified. Slightly silicified gossans are the most common and their structure is less cellular than may be expected, the samples often fracture conchoidally revealing well developed limonites after pentlandite and pyrrhotite.

TYPICAL DESCRIPTIONS

Gossan 35045/B (see Fig. 42, A) has very finely, irregularly mottled, light to dark patches of limonite and silica, common black oxides, occasional blood red patches and rare finely and irregularly interlaminated limonitic yellow to black blebs; voids are of minor significance and are often filled with chalcedonic silica. The surface is smooth with poorly developed conchoidal fractures with minor sharp ridges between fractures.

False gossan 35100 (see Fig. 42, B) shows a network of finely spaced, limonite-stained, quartz veins enclosing voids, some partly filled with limonite and black oxides. Voids constitute up to half a sample. The surface is rough with small jagged projections on the edges of the voids.

Laterite 35592 (see Fig. 42, C) is an open breccia of fragments of rock, part banded or otherwise layered and part structureless, containing various oxides of iron from hematite to limonite, generally subangular, roughly equidimensional in part cemented by metallic or submetallic cement. Minor limonite-lined intergranular voids are present. The surface is irregular with a poorly developed botryoidal texture. This sample is denser than those previously described and is slightly magnetic.

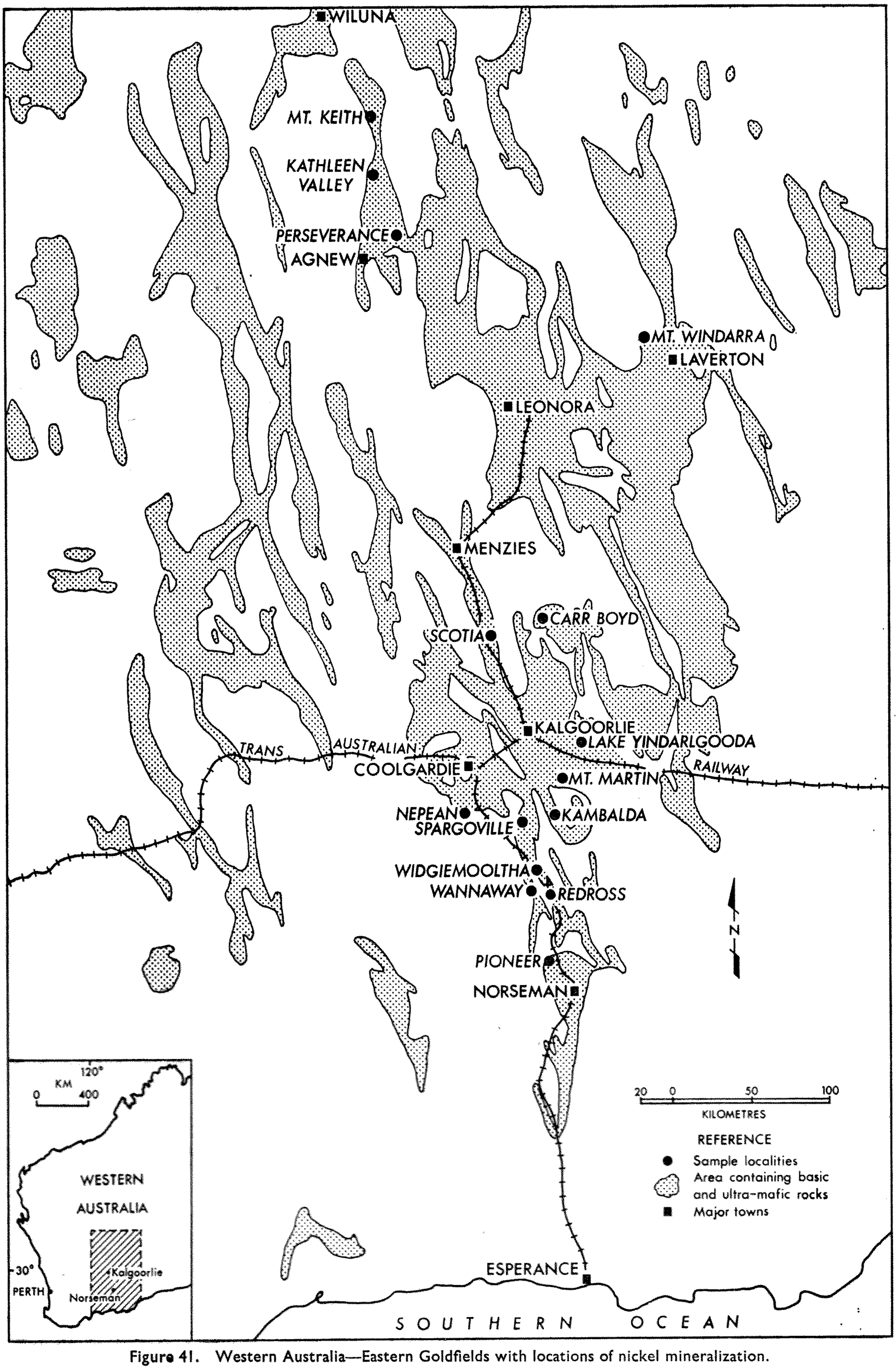

Figure 41. Western Australia—Eastern Goldfields with locations of nickel mineralization.

Figure 42 (opposite)

Photographs of a gossan, a false gossan and laterite

A 35045/B A good example of a silicified nickel sulphide gossan, the mottled surface and minor voids are easily seen.

B 35100 A false gossan derived from pyrite, note the large voids.

C 35592 The cut and polished surface of a laterite with large and small ferruginous accumulations cemented together.

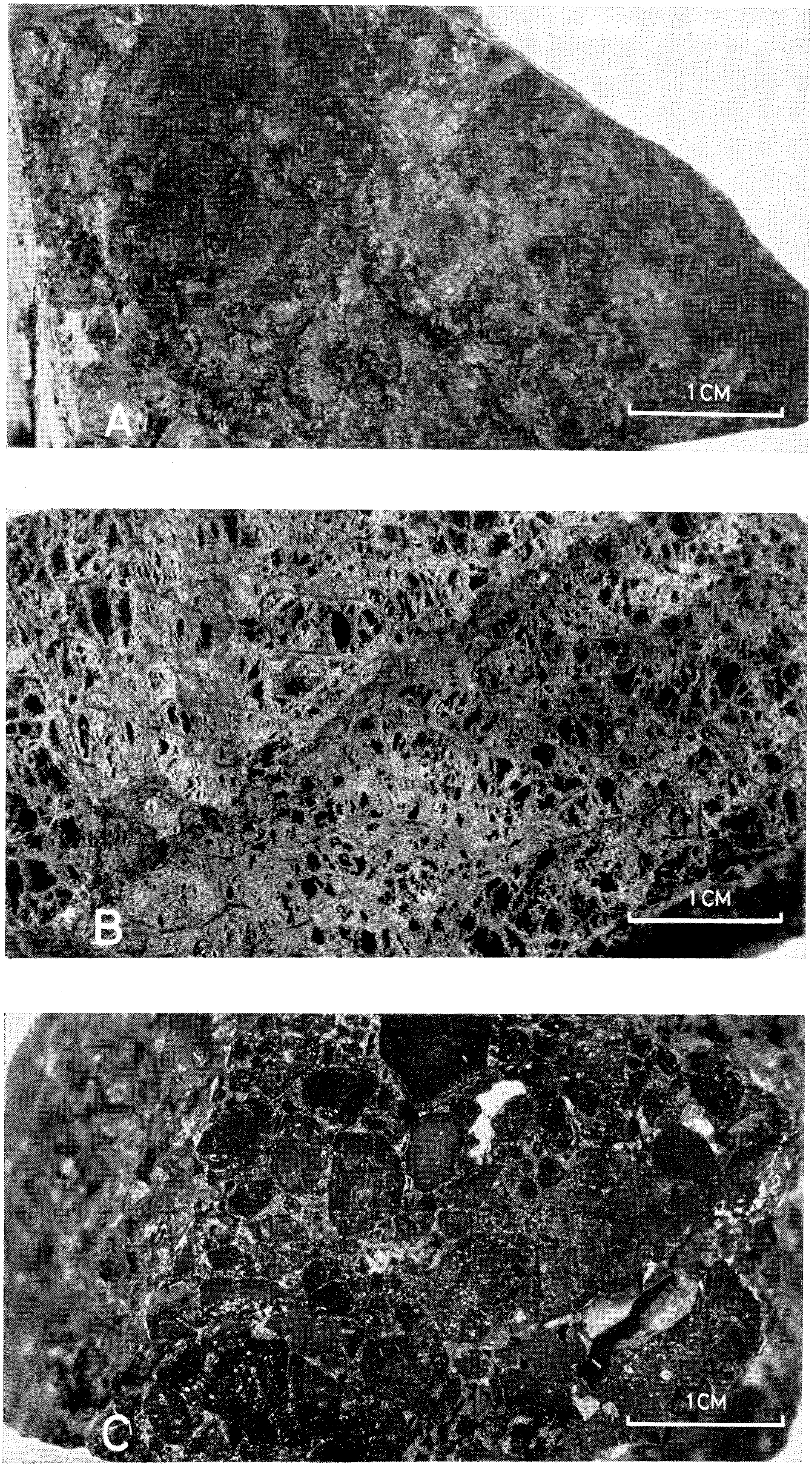

Figure 42

GEOCHEMISTRY

ANALYTICAL TECHNIQUE

The technique employed for analysis was conventional perchloric/nitric acid digestion with evaporation to dryness, followed by aspiration of the residue from a hydrochloric acid solution by Atomic Absorption Spectroscopy (A.A.S.).

Method

Weigh 1 g of ground sample (-200#) into a pyrex test tube (185 mm x 25 mm) add 20 mls of *premixed** concentrated perchloric/nitric acid (3 parts $HClO_4$: 1 part HNO_3).

Place in an air bath and heat to approximately 100C°, allow to remain at this temperature for at least 1 hour. Continue heating until the solution reaches approximately 220°C. Keep at this temperature until it has fumed to dryness. This takes 6 to 8 hours. This time to dryness must be fairly constant if any correlation is to be attempted between chromium results of different batches of samples.

Add 5 ml of concentrated hydrochloric acid and heat on water bath at 100°C for 1 hour. Add 20 ml of distilled water, mix thoroughly and leave to stand overnight.

Determine by A.A.S. using hydrochloric acid (20 per cent) based standards and flame conditions appropriate to the element being determined.

Discussion

This method was chosen as one digestion gave results for a large number of elements with a reasonable degree of reproduceability, as well as being inexpensive in terms of materials and time. This method gives a good "total" value for all elements except chromium, and here if the time for fuming to dryness is kept constant, the results are reproduceable. If "total" chromium results are available from another method, say X.R.F. (X-ray Fluorescence Spectroscopy), for similar samples it is possible to calculate an approximate correction factor to correlate A.A.S. and "total" results.

Other A.A.S. digestion methods such as the use of nitric acid and hydrochloric acids either together or alone, whether fumed to dryness or not, as well as the use of perchloric/nitric acid mixtures not fumed to dryness are not recommended as the results for many elements cannot be easily correlated within "total" results.

INTERPRETATION CRITERIA FOR EACH ELEMENT

Copper

Apart from the presence of nickel itself, the presence of significant quantities of copper must be considered an important guide to nickeliferous gossans. High copper levels imply the presence of sulphide mineralization; copper levels in leached outcrops can be higher than the nickel levels because copper enriches more strongly than nickel in the leaching environment. Copper may also be high in black shales which need not be related to sulphide mineralization although they often are. High copper levels in a gossan appear to be a requirement for economic nickel mineralization at depth. Conversely low copper levels imply the absence of nickel sulphide mineralization. Copper levels of greater than 500 ppm are an indicator of sulphide mineralization.

Lead

Lead levels are usually very low in Archaean rocks from the Eastern Goldfields; if lead is present this may be due to an influx from some later geological source.

The upper background level for lead in the Archaean is approximately 50 ppm.

Zinc

Levels of zinc are generally low in the Archaean greenstones but they are higher in the acid and intermediate volcanics, and volcanogenic sediments, and are usually very high in black shale.

Zinc levels of greater than 1,000 ppm are common in black shale environments which can be close to mineralized greenstones. Consequently care must be taken in interpreting results with high zinc and copper values.

Cobalt

This element has been widely analysed in the course of mineral exploration, but it does not appear to help interpretation as there is no apparent correlation on a regional scale with other elements of interest. Correlation within a given mineralized body may be possible but more work is required on this subject.

Cobalt shows a wide concentration range, commonly with values up to 1,000 ppm.

Chromium

It appears possible that the chromium level can be correlated directly with the degree of lateritization. Chromium is not leached out of the weathered material but builds up with the resistate minerals, usually as chromite.

Levels of greater than 500 ppm are typical in lateritized material.

Manganese

Like lead, primary manganese is usually low in the Archaean, and its presence may be due to an influx from later rocks. Manganese is concentrated in a lateritic environment so high manganese laterites will develop if a source of the element is available. The situation is further complicated because manganese acts as a scavenger of other elements particularly copper, lead, zinc and iron, so care must be taken in interpreting high levels of these elements if high manganese is also present.

Manganese values of greater than 1,000 ppm are not uncommon in lateritized samples.

Silver

Silver is enriched similarly to copper but is itself an indicator for non-nickel sulphide mineralization, particularly that of copper and lead sulphides, so low values are to be expected in the nickel sulphide gossans.

Levels of less than 3 ppm are typical.

Molybdenum

Molybdenum is an enrichment indicator which is a good pathfinder for copper sulphide mineralization, though it is usually absent from nickel sulphide mineralization. Levels of less than 5 ppm are typical.

Iron

High iron levels are usually related to lateritization, with most gossanous material containing less than 30 per cent iron.

Nickel

This element is the prime exploration target; the absence of nickel negates the possibility of nickel sulphide mineralization. Alternatively the presence of significant levels of nickel does not necessarily mean that sulphide mineralization is present. The presence of nickel indicates the presence of ultramafic rocks and laterites as well as sulphide mineralization. Separation may be made as follows:

1. *Nickel sulphide mineralization* is usually present as pentlandite and nickeliferous pyrrhotite, usually with chalcopyrite which is the source of the copper enrichment that is usually found with leached material derived from nickel sulphides.

2. *Weathered ultramafic rocks* commonly contain high levels of nickel, usually derived from olivines in the fresh rock. These are usually separated from the other types as the levels of most other elements are low.

3. *Laterites* derived from ultramafic rocks are characterized by high nickel values, typically 1,000 to 5,000 ppm, but can be very high e.g. greater than 1 per cent nickel. These samples can be separated from nickel sulphide mineralization by their higher iron, chromium and manganese and usually low copper. Laterites grade into weathered ultramafic rocks as they are derived from them.

Analysis of a typical nickel sulphide gossan

	Cu	Pb	Zn	Ni	Co	Cr	Mn	Ag	Mo	Fe
Range of results	500 to 5000	less than 50	less than 100	1000 to 5000	less than 1000	less than 500	less than 500	less than 5	less than 5	10% to 30%
Typical value	950	30	65	2200	300	350	230	3	<5	22%

All results are in ppm except iron which is expressed in per cent.

Description of results

The results of this survey are presented in Tables 20 to 22; space does not permit a detailed discussion of each result but summary remarks and inferences are shown in the relative columns.

*Premixed acids are used to avoid explosion risks, for precautions using perchloric acid see Steere (1972).

TABLE 20. GOSSANS AND RELATED ROCK TYPES

G.S.W.A. No.	Shoot, Prospector Ore Body	Location	Company	Cu	Pb	Zn	Ni	Co	Cr	Mn	Ag	Mo	Fe	Remarks	Inferences
35001	S.L.O.B.*	Kambalda	W.M.C.	630	42	6	165	17	361	20	3	9	1·2	Sulphide gossan‡	
35015/A	Otter Shoot	„	„	17,000	32	33	190,000	2,400	46	234	a	b	26·8	Gaspeite gossan	
35015/B	„ „	„	„	12,000	39	26	200,000	3,500	76	143	a	b	30·3	„ „	
35015/C	„ „	„	„	13,000	39	40	40,000	500	1,250	151	3	5	52·8	„ „	
35017		Mt. Martin	Great Boulder	350	36	116	19,000	76	1,690	652	a	b	9·3	Metasediment adjacent in mineralization	Ni mobilized into sediment
35019	Area 2	„ „	„ „	360	32	340	1,690	108	1,700	2,700	3	b	52·8	Gersdorffite, pyrrhotite gossan	High Zn, Cr and Mn implies lateritized metasediment
35024	Area 8 (south)	„ „	„ „	2,710	33	44	2,820	140	111	134	2	b	47·9	Relict sulphides in gossan	
35026/A		Carnilya Hill	B.H.P.	3,140	88	234	2,590	110	4,500	280	2	b	35·9	Sulphide gossan‡	Possibly lateritized metasediment
35026/B		„ „	„	4,010	52	73	13,000	880	870	236	4	b	51·0	„ „	
35030	J.H. Prospect	Pioneer	Newmont	530	20	5	900	69	280	278	a	8	7·8	„ „	
35033	B.B. Prospect	„	„	500	39	65	520	83	560	2,300	3	b	48·3	„ „	
35035	H.H. Prospect	„	„	2,140	56	2,000	6,000	600	1,260	164	3	14	45·4	Sulphide gossan‡ adjacent to black shale	High Zn confirms black shale.
35037	Mt. Edwards	Widgiemooltha	Inco	780	25	39	1,160	60	450	388	18	b	6·7	Sulphide gossan	High zinc suggests an adjacent black shale or other sediment
35045/A	5B	Spargoville	Selcast	3,310	111	582	7,250	220	650	189	3	5	37·6	„ „	
35045/B	„	„	„	2,680	162	1,100	11,000	415	890	350	4	b	43·9	„ „	
35047/A	5A	„	„	2,550	32	113	10,500	110	1,300	168	2	b	16·8	„ „	
35047/B	„	„	„	1,740	68	58	1,450	67	1,680	152	3	b	21.6	„ „	
35048	Nepean		Metals Expl.	3,010	92	480	7,100	830	2,450	15,000	4	b	47·8	Lateritized sulphide gossan	High Zn, Cr and Mn implies lateritization and mobilization from adjacent metasediment
35071	Scotia		Great Boulder	3,600	24	90	17,000	429	803	1,162	a	b	18·6	Sulphide gossan	
35072	„		„ „	560	13	32	2,080	149	907	1,392	a	b	4·0	Silicified cap rock	
35076/A	Carr Boyd		„ „	2,250	15	17	10,000	376	224	165	a	b	12·7	Sulphide gossan	
35076/B	„ „		„ „	175,000	39	220	8,000	131	344	15	24	b	35·8	„ „	
35077/C	„ „		„ „	9,000	27	27	18,500	340	473	67	4	b	62·0	„ „	
35077/D	„ „		„ „	6,200	24	22	12,500	271	330	54	8	b	56·4	„ „	
35083	Shirley Shoot	Mt. Windarra	Poseidon	6,210	23	53	4,590	214	1,332	3,900	2	b	19·0	„ „	
35089	„ „	„ „	„	3,340	35	280	18,000	188	2,312	868	a	b	17·1	Sulphide gossan from disseminated sulphide adjacent to B.I.F. †	Zn probably from adjacent B.I.F. †
35098/A	Perseverance	Agnew	Selcast	590	16	12	920	39	288	745	a	b	6·6	Sulphide gossan	
35098/B	„	„	„	1,060	23	44	3,230	102	500	453	a	b	25·0	„ „	
35098/C	„	„	„	3,130	29	150	6,350	131	1,298	423	2	b	55·0	„ „	
35100	6 mile prospect	Kathleen Valley	Anaconda	600	14	40	860	48	1,053	149	a	b	16·4	Disseminated sulphide gossan	
35109/A	Mt. Keith		Metals Expl.	500	16	11	1,230	47	431	2,000	a	b	2·6	„ „ „	
35109/B	„ „		„ „	480	40	31	1,040	72	477	1,900	a	b	5·4	„ „ „	
35709/A	Redross	Widgiemooltha	Anaconda	2,030	27	54	1,700	80	2,330	413	2	b	36·7	Sulphide gossan with silicified black shale adjacent	
35709/B	„	„	„	1,240	23	300	520	69	11,500	488	a	b	29·2	„ „ „	High Zn and Cr implies lateritized black shale
35710/A	„	„	„	760	21	215	1,230	72	710	3,450	a	b	13·0	Discovery gossan	High Zn implies black shale
35710/B	„	„	„	620	23	81	570	70	4,330	324	a	b	33·1	„ „	High Zn and Cr implies lateritized shale
35710/C	„	„	„	750	29	48	520	54	890	147	a	b	11·4	„ „	
35710/D	„	„	„	690	19	47	240	21	950	128	a	b	8·0	„ „	
35711/A	„	„	„	1,080	35	68	940	103	560	360	a	b	32·5	Sulphide gossan	
35711/B	„	„	„	1,960	25	26	360	63	870	167	a	b	23·4	„ „	
35711/C	„	„	„	1,870	31	35	250	30	750	396	a	b	18·8	„ „	High Cr implies lateritization
35711/D	„	„	„	1,950	36	66	670	72	2,690	435	2	b	28·1	„ „	„ „ „
35711/E	„	„	„	2,490	30	53	390	53	2,720	214	a	b	22·2	„ „	„ „ „
35711/F	„	„	„	760	27	38	180	46	1,750	229	a	b	25·8	„ „	
35711/G	„	„	„	790	30	45	320	51	1,120	393	a	b	22·0	„ „	

TABLE 20. GOSSANS AND RELATED ROCK TYPES—continued.

G.S.W.A. No.	Shoot, Prospector Ore Body	Location	Company	Cu	Pb	Zn	Ni	Co	Cr	Mn	Ag	Mo	Fe	Remarks	Inferences
35712	Dordie Rocks	Widgiemooltha	Anaconda	810	53	77	3,770	173	650	173	7	77	33·4	Sulphide gossan	
35713	,, ,,	,,	,,	790	53	1,104	5,500	120	60	497	5	126	49·0	,,	
35714	,, ,,	,,	,,	1,940	84	51	5,000	347	1,830	94	7	80	45·5	,,	
35715	,, ,,	,,	,,	600	76	48	610	1,400	740	38	10	47	37·4	,, N.B.	
35716	,, ,,	,,	,,	1,520	77	91	55,000	746	670	552	6	69	27·0	,, High Mo	
35717	,, ,,	,,	,,	3,160	70	746	6,180	264	21,000	1,114	7	42	39·0	,,	High Cr and Zn implies lateritized shale
35718	,, ,,	,,	,,	860	72	65	43,500	479	790	479	7	99	19·8	,,	
35719	,, ,,	,,	,,	1,170	31	608	1,560	35	290	49	a	34	8·4	,,	High Zn implies black shale
35720	Widgie No. 3	,,	,,	5,070	48	39	16,000	235	840	87	2	b	41·0	,, ,, ...	High Zn and Cr implies lateritized black shale
35721	,, ,,	,,	,,	120,000	42	422	12,000	466	20,000	615	7	b	27·7	,, ,, ...	High Zn due to ZnS with Cu
35722	,, ,,	,,	,,	5,290	28	42	55,000	719	250	67	2	b	35·4	,, ,, ...	High Zn and Cr implies lateritized black shale
35723	,, ,,	,,	,,	2,200	46	254	25,000	614	3,440	268	a	b	10·9	,, ,,	
35724	,, ,,	,,	,,	3,910	28	30	36,000	1,100	150	196	2	b	49·0	,, ,,	
35725	,, ,,	,,	,,	4,060	34	120	33,000	149	330	307	2	b	22·2	,, ,,	
35726	Wannaway	,,	,,	1,400	23	164	5,800	94	420	220	a	b	15·0	,, ,,	
35727	,,	,,	,,	400	14	73	1,740	33	510	177	a	b	4·6	,, ,,	
35728	,,	,,	,,	4,190	37	290	17,000	307	970	126	a	b	29·8	,, ,, ...	High Zn implies black shale
35729	Redross	,,	,,	3,700	42	96	5,130	317	410	334	3	b	53·0	,, ,,	
35730	,,	,,	,,	1,300	38	65	560	120	830	4,500	a	b	24·0	,, ,,	
35731	,,	,,	,,	1,310	39	142	3,830	237	3,230	240	2	b	34·2	,, ,, ...	High Cr implies lateritization
35732	,,	,,	,,	1,640	30	98	950	109	2,530	158	a	b	24·4	,, ,, ...	,, ,, ,,
35733	,,	,,	,,	3,770	61	299	3,630	232	2,840	285	3	b	55·6	,, ,, ...	High Zn and Cr implies lateritized black shale
35737/A	Wannaway	,,	,,	490	12	50	1,960	135	320	576	a	b	4·4	Siliceous sulphide gossan	Low Fe due to silicification
35737/B	,,	,,	,,	1,910	14	134	5,120	1,000	180	4,000	a	b	11·3	,, ,, ,,	High Cr implies lateritization
35737/C	,,	,,	,,	630	13	55	2,180	116	460	583	a	b	5·7	,, ,, ,,	Low Fe due to silicification
35737/D	,,	,,	,,	510	15	42	1,680	22	240	226	a	b	5·7	,, ,, ,,	,, ,, ,,
35745/A	,,	,,	,,	760	20	54	4,390	181	1,040	660	a	b	4·6	,, ,, ,,	,, ,, ,,
35745/B	,,	,,	,,	680	18	48	3,690	178	920	734	a	b	4·9	,, ,, ,,	,, ,, ,,

All results in parts per million, except iron which is shown as per cent.
a = less than 2 parts per million
b = less than 5 parts per million

* Silver Lake Ore Body
† Banded Iron Formation
‡ Sulphide gossan means nickel sulphide gossan

TABLE 21. SULPHIDE ORE AND RELATED SAMPLES

	Ore Body etc.	Location	Company	Cu	Pb	Zn	Ni	Co	Cr	Mn	Ag	Mo	Fe	Remarks
35038	Mt. Edwards	Widgiemooltha	Inco	2,680	55	20	95,000	2,300	270	39	5	b	53·5	Massive sulphide ore
35040	,, ,,	,,	,,	3,800	52	46	50,000	1,400	350	273	5	b	34·6	Coarse interstitial ore
35043	,, ,,	,,	,,	190	26	128	3,780	141	930	1,398	a	b	7·4	Disseminated sulphide ore
35050	No. 3 Sill contact	Nepean	Metals Expl.	44,000	52	23	74,000	4,600	170	22	19	b	46·3	Massive sulphide ore
35051	No. 3 Sill F/W contact	,,	,, ,,	5,140	40	21	140,000	5,300	720	61	5	b	42·4	,, ,, ,,
35052	No. 2 Lens	,,	,, ,,	39,000	24	499	80,000	800	1,810	147	11	b	21·6	,, ,, ,,
35068	830 ft. level	Scotia	Great Boulder	4,390	35	138	64,000	624	480	843	3	b	17·1	,, ,, ,,
35069	,, ,,	,,	,, ,,	3,090	32	91	70,000	800	210	676	3	b	22·1	Disseminated sulphide ore
35080		Carr Boyd	,, ,,	30,000	22	112	9,410	515	140	136	6	b	15·3	Mineralized norite
35081		,, ,,	,, ,,	5,090	32	25	43,000	1,200	80	52	3	b	36·1	Massive sulphide ore
35082		,, ,,	,, ,,	2,690	28	33	19,000	658	290	170	3	b	27·1	,, ,, ,,
35084	A Shoot	Mt. Windarra	Poseidon	1,410	46	108	60,000	638	790	343	4	b	45·0	Breccia sulphide ore
35087	,,	,, ,,	,,	1,970	39	159	12,000	163	680	311	7	44	13·1	Sulphide ore in talc schist
35088	,,	,, ,,	,,	1,880	42	77	17,000	249	1,430	2,000	2	b	10·5	Disseminated sulphide ore
35096	Perseverence	Agnew	Selcast	930	28	74	24,000	435	400	867	a	b	14·0	Massive secondary sulphide ore con- *taining violarite*
35097	,,	,,	,,	1,340	33	17	77,000	1,500	440	188	3	b	54·8	Massive primary sulphide ore
35099	,,	,,	,,	920	29	80	23,000	444	280	946	2	b	16·5	Disseminated sulphide ore
35113		Mt. Keith	Metals Expl.	190	20	27	4,970	199	620	273	a	b	3·3	Secondary sulphide ore
35114		,, ,,	,, ,,	150	19	22	4,740	155	430	306	a	b	5·0	Secondary sulphide ore
35115		,, ,,	,, ,,	160	23	22	4,810	143	460	249	a	b	5·5	Primary sulphide ore
35119	No. 5 level Lunnon Shoot	Kambalda	W.M.C.	1,940	49	50	59,000	788	520	1,100	3	b	36·9	Disseminated sulphide contact ore
35748	Perseverance	Agnew	Selcast	1,120	31	27	86,000	1,450	280	157	2	b	43·4	Disseminated secondary sulphide ore with violarite
35749	,,	,,	,,	10	21	21	2,610	82	340	628	a	b	4·4	Serpentinite with violarite and pyrite
35750	,,	,,	,,	660	27	50	17,000	333	160	411	2	b	14·9	Primary sulphide matrix ore
35751	,,	,,	,,	410	29	40	20,000	433	180	428	2	b	17·1	Primary disseminated sulphide ore
35752	5A	Spargoville	,,	3,610	47	86	60,000	1,000	210	378	4	b	35·0	Primary matrix sulphide ore
35753	,,	,,	,,	680	27	47	18,000	302	750	121	a	b	5·7	Primary disseminated sulphide ore
35754	,,	,,	,,	3,410	43	33	77,000	1,280	40	133	5	b	48·6	Primary massive sulphide ore

All results in parts per million, except iron which is shown as per cent.
a = less than 2 parts per million
b = less than 5 parts per million

TABLE 22. LATERITES, FALSE GOSSANS AND RELATED ROCKS

G.S.W.A. No.	Location	Company	Cu	Pb	Zn	Ni	Co	Cr	Mn	Ag	Mo	Fe	Remarks
35006	Kambalda	W.M.C.	430	100	106	14	17	361	20	3	9	1·2	Chert
35031	Pioneer	Newmont	90	21	64	730	6	30	30	a	b	0·1	Magnesite "Ni" scavenger
35065	Lake Yindarlgooda	....	580	34	349	40	27	147	355	4	b	26·3	False gossan
35094/A	Mt. Windarra	Poseidon	510	16	430	119	15	275	1,157	a	b	5·6	B.I.F.*
35094/B	Mt. Windarra	Poseidon	20	18	362	30	10	280	1,180	a	b	4·1	B.I.F.*
35111	Mt. Keith	Metals Ex.	810	39	280	3,520	140	2,200	371	3	b	64·0	Ferruginous laterite
35112	Mt. Keith	Metals Ex.	570	29	50	450	62	11,000	114	3	b	64·1	Ferruginous laterite
35584	Leonora (1:250,000)	....	50	28	289	170	98	180	250	3	b	57·7	Ferruginous laterite
35585	Leonora (1:250,000)	....	200	35	78	120	49	710	68	3	b	38·3	Laterite
35592	Leonora (1:250,000)	....	20	32	19	140	62	1,580	223	4	b	58·9	Ferruginous laterite

*Banded Iron Formation.

All results in parts per million, except iron which is shown as per cent.
a = less than 2 parts per million
b = less than 5 parts per million

Table 20 gives the analysis of typical gossans; Table 21 contains analyses of the sulphides from which the gossans were derived: Table 22 presents false gossans, laterites and other non-economic derived samples.

Special comment is made of samples 35712 to 35719 (Table 20) from Dordie Rocks; these as a group contain very high molybdenum. Also, samples 35094/A and 35094/B (Table 22), though described as banded iron formations from field occurrences, cannot be so (sensu stricto) as the iron content is too low. They would probably be better described as surface iron-enriched sediments with banding.

It is worthy of note that significant variations in results have been obtained from the analysis of separate pieces of the same sample and that samples from the same general location are similarly variable. Localized leaching effects may have been very important in the development of this material.

CONCLUSIONS AND RECOMMENDATIONS

SAMPLING

The collection of samples for gossan analysis must be undertaken with consideration for the physical and chemical characteristics described. When collecting, sample all ferruginous material approximating the physical descriptions presented earlier. If possible collect a few samples from each outcrop and a few from adjacent outcrops. Ensure that all samples are analysed. The analysis of a moderate number of samples (say 10) is necessary to overcome the variability of individual samples; multiple sampling is much better than bulking the samples and treating them as a single analysis. Bulking automatically gives an average which reduces the geochemical contrast and it is the contrast that gives rise to an anomaly.

ELEMENTS DETERMINED

It is considered that the following elements at least should be determined: Copper, lead, zinc, nickel, chromium, manganese, and iron. If fewer than those are analysed it would be possible to miss a significant anomaly. It may be worthwhile to analyse for other elements but many detailed analyses are necessary to fully evaluate them.

ANALYTICAL METHOD

The method described here is recommended, though any other method that yields a "total" element result would be satisfactory.

SUMMARY OF INFERENCES

1. Gossans developed over nickel sulphide mineralization are characterized by high copper and nickel results.

2. High zinc results may be due to the presence of sediments especially black shales.

3. Lateritized samples are commonly characterized by high chromium, manganese and iron.

Little correlation appears possible with cobalt, silver and molybdenum. Lead is normally low in all samples.

CONCLUSION

From the collection and analysis of multiple samples from leached outcrops related to nickel sulphide, it is possible to establish criteria for the separation of true gossans from false gossans and laterites.

ACKNOWLEDGMENT

The assistance obtained from the various companies in collecting these samples is appreciated as is that freely given by members of the Mineral Chemistry Division of Government Chemical Laboratories who carried out the analytical work.

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A PILOT STUDY OF PHOSPHORUS DISTRIBUTION IN PARTS OF THE BROCKMAN IRON FORMATION, HAMERSLEY GROUP, WESTERN AUSTRALIA

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ABSTRACT

Electron microprobe examination of core from the Dales Gorge Member of the Brockman Iron Formation confirmed that the bulk of the phosphorus is present as apatite; but some of the matrix minerals also contain traces of phosphorus, and rare grains of monazite were detected. A phosphate stain printing technique using a one-solution molybdate-ascorbic acid-based reagent, was developed and used to determine the phosphate distribution in some 110 m of drill core from a number of separate holes. The vertical distribution is variable but is typically banded on a scale similar to the mesobanding, but to some extent independently of it. While imperfect lateral continuity can be traced over a number of holes in a restricted area, striking anomalies are present in equivalent sections 80 km apart. There is no obvious correlation between phosphate concentration and specific mesoband type, but cyclic phosphate occurrence is present in several cyclothem sequences. The distribution may best be explained

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by erratic influx of phosphate into the basin and local biochemical precipitation, although migration of phosphate during or after consolidation may also be involved. This pilot study did not include quantitative determination of phosphorus present in the iron formation.

INTRODUCTION

SUMMARY OF GEOLOGICAL BACKGROUND

The 2,000 million year old Hamersley Group, with a usual thickness of 2,400 m, is typified by an abundance of banded iron formation, which is interstratified with shale, dolomite and acid lava, and at some levels intruded by thick dolerite sills. Its present outcrop area is bounded approximately by latitudes 21° to 22°S and longtitudes 116° to 120°E. The group, as originally defined by MacLeod and others (1963) and amended by Trendall and Blockley (1970), is subdivided as follows:

Boolgeeda Iron Formation
Woongarra Volcanics
Weeli Wolli Formation
Brockman Iron Formation — Yandicoogina Shale Member, Joffre Member, Whaleback Shale Member, Dales Gorge Member
Mount McRae Shale
Mount Sylvia Formation
Wittenoom Dolomite
Marra Mamba Iron Formation

Important hematite ore bodies lie within both the Joffre and Dales Gorge Members of the Brockman Iron Formation. The Dales Gorge Member was formally defined by Trendall and Blockley (1968), using 142.11 m (466.25 feet) of core largely from a single hole (47A) at Wittenoom as the type section. Blockley (1969) has illustrated clearly the stratigraphic equivalence of the unenriched Dales Gorge Member and the hematite ore derived from it by metasomatic replacement.

The terminology in this report follows that of Trendall and Blockley (1970) but three of their terms will be explained here to allow independent reading of this paper.

1. Macrobanding: the Dales Gorge Member is divided into 33 marcrobands, consisting of BIF O to BIF 16, made up of iron formation, alternating with S1 to S16 which are generally thinner and consist of shale, chert and siderite.

2. Mesobanding: the conspicuous striped succession of internally consistent bands of different composition, with an average thickness of less than about 3 cm, present in the iron formation, and seen prominently in cores figured in this paper despite the reduced scale of the photographs. Trendall and Blockley (1970) classify mesobands on the principal mineral constituent, rather than using a more detailed but unwieldy classification involving the known combinations of the iron formation minerals.

3. Microbanding: an alternation, typically within chert mesobands only, of regular repetitive laminae of even thickness, usually within the range 0.3 to 1.7 mm and defined by varying content of some iron-bearing mineral.

RATIONALE, SCOPE AND OBJECTIVES OF THIS STUDY

The small amount of published data on phosphorus content of Hamersley Group iron formations indicates an average of about 0.14 per cent P (Trendall and Blockley, 1970). Different deposits of high-grade hematite within them are known to vary from 0.03 per cent P to O.15 per cent P (MacLeod 1966), but material of the latter kind is not currently saleable as ore. Little is known of the movement of phosphorus during the enrichment process, and as a foundation for a study of this, a survey was undertaken of the form of occurrence, and the distribution, of phosphorus in selected sections of the Brockman Iron Formation from which fresh core material was available and which were known to contain important hematite ore bodies.

The form of phosphorus occurrence was first studied using an electron microprobe; after this had established that the bulk of the phosphorus is present as apatite the distribution of phosphate was studied using a stain printing technique, which was developed for the purpose. This technique, and the results of both phases of the investigation, are described in this paper.

The work was carried out in the Division of Mineralogy, Commonwealth Scientific and Industrial Research Organisation, with the active cooperation of the Geological Survey of Western Australia.

MATERIAL USED

The bulk of the material used in this investigation was drill core from a single hole (Hole 47) near Wittenoom, drilled as part of an exploration programme for crocidolite (Trendall and Blockley, 1970). This hole penetrated parts of the Joffre and Dales Gorge Members and the whole of the Whalèback Shale Member. Selected sections of the resultant core, totalling about 86 m, are exhibited in stratigraphic sequence as 48 vertically sawn and polished half-core columns, each about 180 cm high, mounted permanently in the wall of the entry area of the Geological Survey on the 5th floor of Mineral House, Adelaide Terrace, Perth. The undisplayed parts of this sawn core are preserved by the Geological Survey for detailed studies of this kind.

The whole of the undisplayed half of column 1 of this wall exhibit was prepared for the electron microprobe study, but only part was examined. The column comes from the BIF 4 macroband of the Dales Gorge Member, just below the S5 macroband.

The stain printing was carried out on the actual displayed surface of the wall exhibit, which includes part of the Joffre Member, a small section of Whaleback Shale Member, and all or part of the following Dales Gorge Member macrobands: BIF 4, S5, BIF 5, S6, BIF 11, S12, BIF 12, S13, BIF 13, S14, BIF 14, S15, BIF 15, S16, and BIF 16. A further 20 m of core selected from several different holes for lateral correlation was also treated, and the phosphate prints photographed alongside their respective cores. This material includes some equivalent sections of the Dales Gorge Member BIF 2 macroband from Holes 20, 28, 33, 40, 46, and the type section all near Wittenoom, as well as short sections from Junction Gorge, 80 km to the east, and their equivalents from the type section.

ELECTRON MICROPROBE RESULTS

APATITE

Qualitative data from the electron microprobe indicate the mineral is a calcium phosphate with chlorine and fluorine below the detection limit of the instrument; it is therefore probably a hydroxyapatite.

In general the individual apatites seldom exceed 20/u in diameter, and are commonly very much smaller. Some of the main textural varieties have been described by Trendall and Blockley (1970), whose figure numbers are referred to in the immediately following text, and with the exception of the type shown in their Figure 35C all have been observed in the material examined. Since many of the grains are below 5/u and closely associated with varied fine-grained matrix minerals it is not always possible to categorize them. In addition to the fine spots in chert (Fig. 35, F) the probe has detected similar specks in stilpnomelane (common), minnesotaite (sometimes) and riebeckite (rare).

There is a general tendency for a single P-band* to contain the same apatite form; thus 1-2/u spots may be the major feature of one P-band, 5-15/u clear euhedra another, and so on. The richer P-bands often contain the skeletal forms shown in

* See definition on page 78.

Figure 35, A, and in high concentrations these may form a semi-continuous network anastomosing through the chert. In one chert-carbonate meso-band which was virtually free of phosphate, tiny apatite spots were found in the chert centres of a few of the "atoll" textured ankerites which were a common feature of this band.

Despite the variety of forms present in the samples it seems possible to divide them into three main groups:

(1) The globular and cigar-shaped forms with turbid centres, (Fig. 35, D and E). (The fine dusty inclusions have been identified as some form of iron oxide with the probe).

(2) The fine anhedral spots included with the matrix minerals such as chert (Fig. 35, F).

(3) The interstitial forms such as the clear 5-15/u euhedra, and the skeletal forms (Fig. 35, A). Some implications of this division are discussed later in this report.

RARE EARTH PHOSPHATE

Traces of a rare-earth phosphate were found in some samples. Qualitative results indicate this is a thorium-free monazite, and observations in reflected light suggest the mineral is probably diagenetic but may represent reorganized detrital material.

Since most of the probe work was aimed at examining the distribution of phosphorus in the bands, rare earths were monitored only in a few specimens and thus the distribution is still unknown. However it is unlikely that anything more than traces are present.

PHOSPHORUS IN THE MATRIX MINERALS

In general the phosphorus content of the magnetite, hematite, carbonates and silicates is close to the detection limit of the probe. Typical results showed a small positive count over the background values, but the standard deviation is commonly twice that of the values obtained, for example 0.01 $\pm$ 0.02 per cent. In apatite-rich bands, counts for phosphorus in the associated minerals rise significantly. However this may well be backscatter from the closely attendant apatite, and further study is needed. Phosphorus was not detected in chert (i.e. quartz).

PHOSPHATE STAIN PRINTING: TECHNIQUE

The folowing method is based mainly on a modification of a one-solution reagent described by Murphy and Riley (1962) for photometric analysis of phosphate in natural waters and on standard chromatographic techniques.

REAGENTS

(1) Ammonium molybdate (4 per cent in H_2O)

(2) Nitric acid 5N.

(3) Potassium antimonial tartrate (O.3 per cent in H_2O) (Stabilizing agent).

(4) Ascorbic acid (2 per cent in H_2O) (Reducing agent).

The reagents are prepared as stock solutions with the exception of ascorbic acid which is freshly made before use.

These are mixed in the following sequence:

25 parts (1) mixed thoroughly with

20 parts (2)

3 parts (3) added and mixed.

15 parts (4) added and mixed.

These ratios are not critical. In some situations (i.e. high phosphate) the molybdate could be decreased to aid resolution. Depending on the temperature the mixture is stable for several hours, but it is best to prepare small quantities at intervals of 2-3 hours or less, when printing large areas.

SUBSTRATE

The ideal material for stain printing would be a thin, soft, strong membrane, finely porous but not permeable, capable of holding the optimum amount of solution and limiting diffusion to the immediate vicinity of the test grains.

Treated photographic papers and films (Williams and Nakhla, 1951) were found to be useful for small, smooth surfaces, although carbonate effervescence tends to lift these impervious membranes from the surface and to spread the stain; but for the large-scale tests involving tens of metres of core, resolution was sacrificed for convenience. For this project 5 cm wide rolls of Whatman No. 1 chromatographic paper were used. For the first trial runs the paper was surfaced with methyl cellulose (to limit diffusion of the stain), but considerable difficulty was experienced in preparing consistent coats over long lengths, and the technique was abandoned for the bulk of the project. Resolution with this methyl cellulose surfaced paper approaches that of the photographic emulsions, but satisfactory results for this general study were obtained with untreated paper.

PROCEDURE

1. A smooth, preferably polished surface, produces the best results but adequate resolution for most purposes can be gained from the outer surface of untreated core.

2. The surface should be thoroughly cleaned, avoiding the use of phosphate based detergents.

3. Impregnate the required length of paper strip with test solution. The reagent applicator used for this project is illustrated in Figure 43. The paper should be damp, not wet, but the required dampness can only be determined by trial. The paper may be left to dry for several minutes without affecting the process.

4. The treated strip is laid on the core, covered with clean paper towelling and rolled with a rubber roller to give a close contact with the surface and to remove excess reagent. Curved sections (e.g. uncut core) are treated in the same manner except that instead of rolling, a strip of foam plastic covered with thin polythene is laid over the covering paper and presed firmly against the core with a semi-circular portion of a tube, (a cardboard tube cut longitudinally is satisfactory). Contact time is a matter of experiment, and will depend on how much reagent is present in the test strip; 10-15 seconds is usually adequate. On flat surfaces or where the strip remains in close contact with the specimen the developing blue stain can be examined by removing the covering paper. However, with curved surfaces it is best to retain the pressure for a fixed time to produce an even finish.

5. Having struck a balance between time of contact and diffusion of the stain, the strip is removed. The stain will continue to develop, reaching a maximum intensity within a minute or so, but will also continue to diffuse. Photographing the strip at the optimum moment seems to be the best method of preserving a permanent record.

The process may be repeated several times with fresh strips without loss of detail on smooth surfaces, but less effectively on the relatively porous surface of untreated core.

Once the strip has dried, the deep blue colour of the molybdate stain will fade, the particularly rich areas then forming a bluish green effect apparently due to the potassium antimonial tartrate. Without this stabilizing component the molybdate blue will oxidize to a pale yellow colour due to the action of the nitric acid.

The original deep blue colour can be recovered by spraying the strips with 1 to 2 per cent ascorbic acid solution, but further diffusion may occur and sometimes an overall blue stain will obscure the detail. Bright light also produces confusing blue stains, so that once the acid has been allowed to disperse, the strips should be stored in the dark.

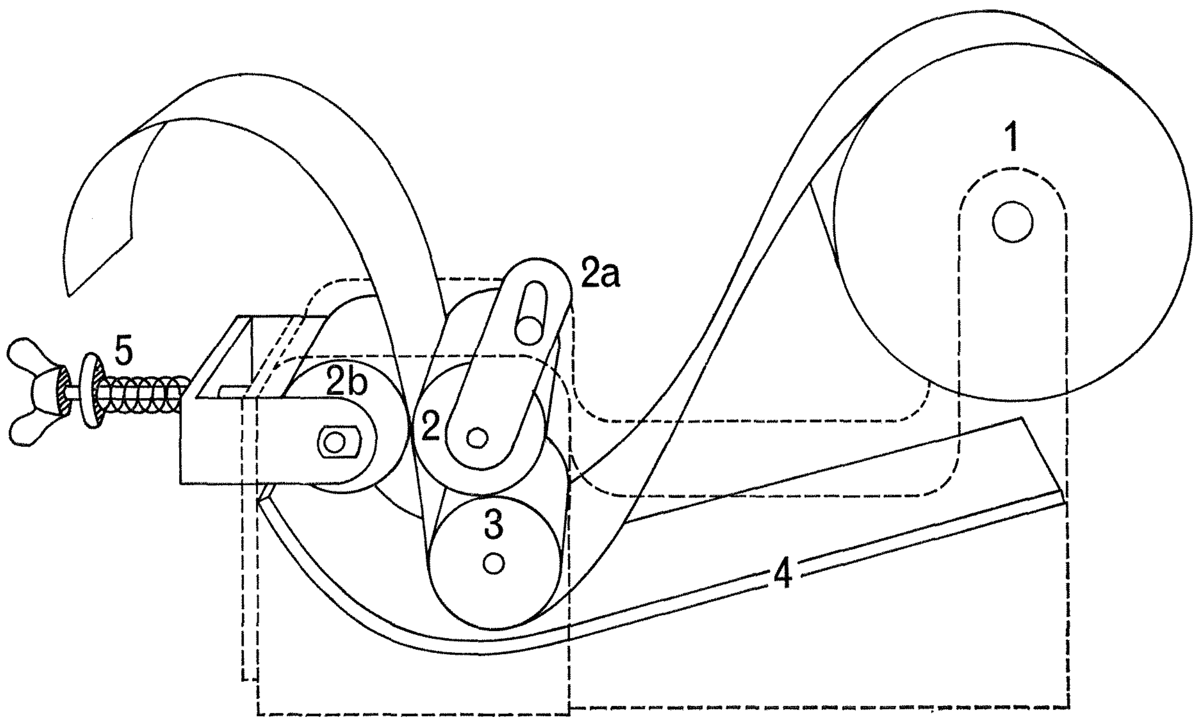


Figure 43. Reagent applicator for large scale stain printing of core. The device is made from acrylic sheeting, and the rollers from acrylic bar, using stainless steel accessories.

To start the process, the free end of the paper is moistened and placed in contact with the driving roller (2). Rotation of the handle (2a) draws the paper between the two rollers (2 and 2b). The free roller (3) is placed into the bath (4) on top of the paper, keeping it immersed in reagent. Roller pressure is adjusted (5) to squeeze out excess reagent.

Strips about 120 cm long are the maximum that can be conveniently handled, and the first 10 to 20 cm of this are discarded since they are usually too wet for use after standing in the reagent for some time.

The technique as described is still in a crude form and could undoubtedly be improved. Nevertheless, when treating small sections the method can resolve grains of the order of a few microns and by drying the paper in a blast of warm air, diffusion can be effectively limited. This printing method is not necessarily restricted to banded iron formation of for that matter to apatite. It could be used for virtually any acid soluble phosphate. At the acid strength used here the test is specific for phosphate in the presence of silica. Elements such as arsenic have not been tested. Perspiration reacts with the reagent damped paper to produce a blue stain and tobacco ash also produces some interesting anomalies. As a skin protection and to avoid finger printing the paper polythene gloves were worn during the process.

PHOSPHATE STAIN PRINTING: RESULTS

A selection of typical core segments with their corresponding phosphate prints is illustrated in Figures 44, 45 and 46.

Figures 44, 45, and 46 show a selection of core photographs with matching phosphate prints prepared from an exhibit of vertically sawn and polished Brockman Iron Formation core from Hole 47 at Wittenoom. The phosphate print is the left hand member of each column pair, and shows the phosphate (apatite) distribution laterally reversed with respect to the parent core. The core has a nominal diameter of 2⅛ in. (5.4 cm). The column numbering of the figures corresponds with that of the exhibit. The phosphate print was photographed alongside a scale marked from 0 to 180 cm, with the zero marking the base of each column. The scale is included in the figures for convenient reference. The polished core is bedded in portland cement, and breaks and other imperfections are seen in the core photographs, and to some extent mirrored in the phosphate prints, as white lines and markings.

These prints clearly show the marked banding of the apatite distribution, and the wide variation in the type and intensity of the bands. Due to problems of reproduction it may not always be possible to see the remarkable conformity between lithology and phosphate distribution, but in many cases the phosphate prints accentuate features not readily seen on the polished surfaces themselves. Under optimum conditions the prints accurately show the distribution of small individual apatite grains. However as the phosphate content of a layer increases, the spots coalesce, and at some unknown value (possibly 5 or more per cent apatite) a continuous ribbon of colour is produced. It is difficult to apply quantitative judgements to the prints since carbonate effervescence, excessive reagent and contact time all tend to increase diffusion of the stain.

To avoid nomenclatural confusion, the term P-band is applied to a stratigraphic horizon defined by the presence of sufficient phosphate to produce a distinct band of colour on the phosphate print, contrasted against whatever background level is present. In discussion, the term P-band may also be applied to the print itself but the context will make this clear.

Figure 44 (opposite)

Phosphate distribution in parts of the Dales Gorge Member, Hole 47 at Wittenoom

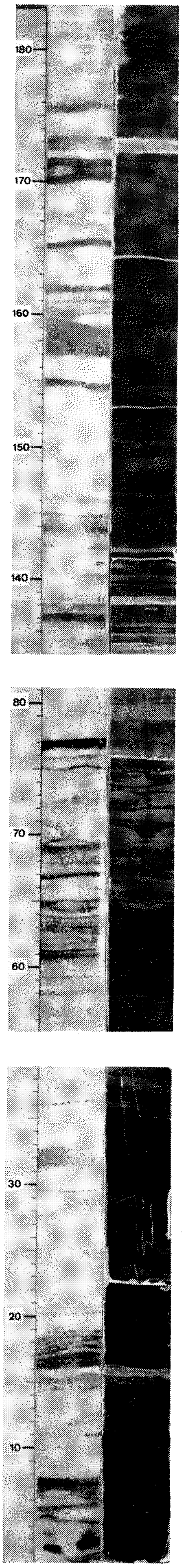
Column 1. Part of the BIF 4 macroband just below the S5 macroband. The undisplayed half of this column was used for electron probe studies.

Column 2. 0–81 cm BIF 4
81–145·6 cm S5
145·6 cm to top BIF 5

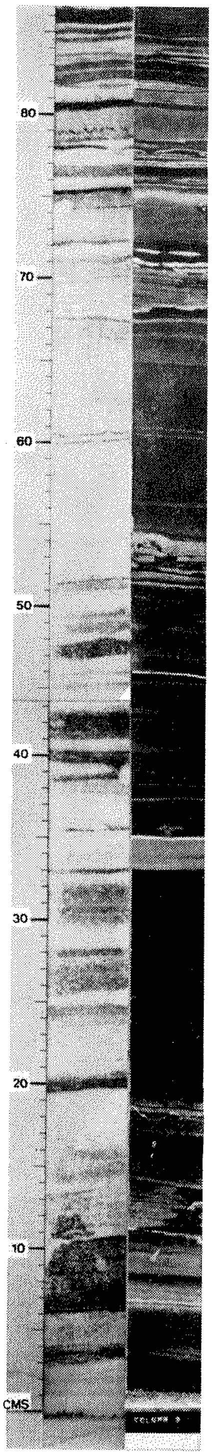
It can be seen that there is no significant difference between the phosphate distribution in the three macrobands represented in this column.

Column 3. BIF 5.

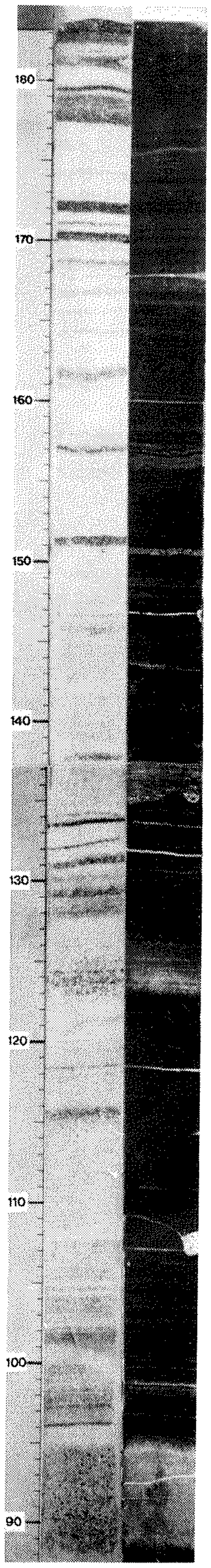
Column 4. BIF 5. The central part of this column contains a podded zone accentuated by the variations in the phosphate print.



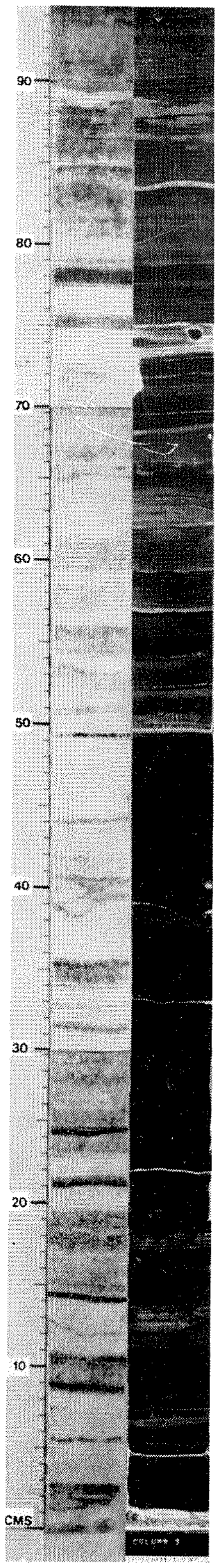
Column 1



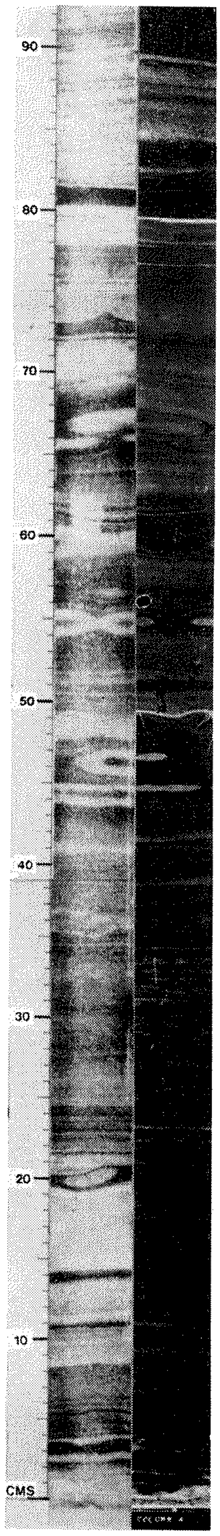
Column 2



Column 2



Column 3



Column 4

Figure 44

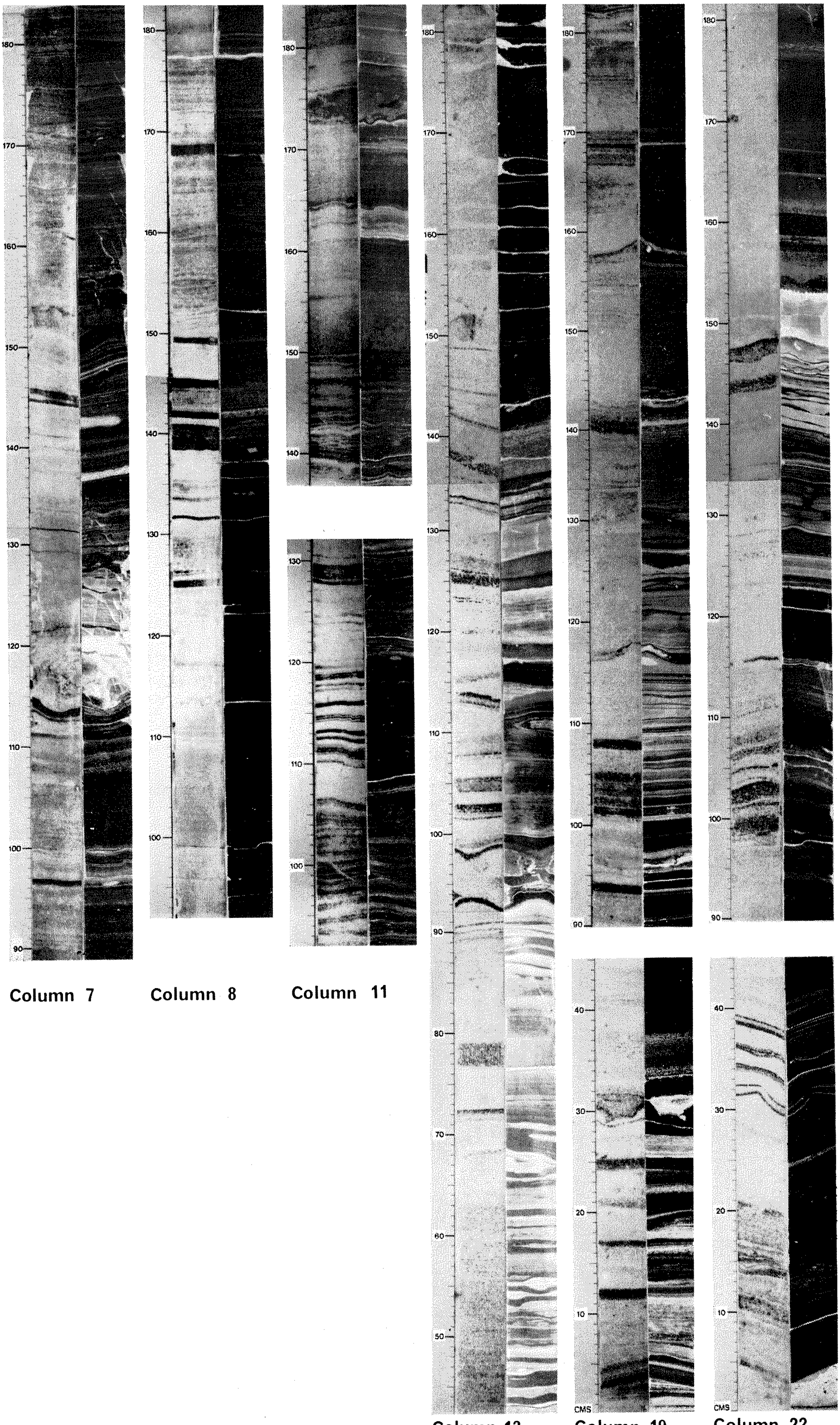

Column 7
Column 8
Column 11
Column 13
Column 19
Column 22
CMS
CMS

Figure 45

VERTICAL PHOSPHATE VARIATION IN BIF MACROBANDS

The most striking feature of the phosphate prints is the marked banding of the phosphate distribution. P-bands as defined above may be of single-grain thickness, and correspond exactly with the mircobands within chert mesobands, or they may extend up to several centimetres, and include minor internal fluctuations. In addition the prints may show diffuse zones (which may include P-bands) with varying, but low levels of colour intensity, as well as zones too low in phosphate to produce significant colouration.

Although one or both edges of a P-band may coincide with mesoband boundaries, so far no clear correlation between phosphate and a specific mesoband type or even a mesoband group has been found. There is, however, good evidence for a cyclic deposition in some zones where the cyclothems are well developed. For example, one Calamina cyclothem group of BIF 16 appears in column 34 of the wall exhibit (Fig. 46, A). The print of this column shows a remarkably symmetrical phosphate distribution matching the various bands of the cyclothems.

One of the interesting features of the prints is seen within podded zones, and zones of slumping and brecciation, where the phosphate distribution follows the contortions with remarkable precision. Some of these appear in Figure 46, C.

There is a clear difference between phosphate prints of the Dales Gorge Member and of the part of the Joffre Member included in the wall exhibit. Typical prints of the latter appear in Figure 46, B and reveal the dominance of narrow rich P-bands separated by low-phosphate zones, unlike the much more varied Dales Gorge Member prints If these prints are typical of the entire member, it would appear that the Joffre Member has a lower total phosphate content than the Dales Gorge Member and that the lithological differences between the two members categorized by Trendall and Blockley (1970) are also reflected in the phosphate distribution.

LATERAL PHOSPHATE DISTRIBUTION IN BIF MACROBANDS

To test the lateral continuity of P-bands a number of correlative core sections from different drillholes up to 5 km apart in the Wittenoom area were stain printed; in general, there is excellent correspondence of mesobanding, though podding and some core gaps prevent perfect correlation throughout. It was not possible in the time available to devise an objective and quantitative technique of matching prints, but a qualitative judgement suggests that at least half of the P-bands can be traced between cores of different holes. While the failure to correlate certain P-bands between holes may be due to mis-matching of mesobands this explanation is unlikely to cover all such instances; also, the undoubted lack of P-band continuity over 80 km, described below, lends credence to the view that much of the observed P-band discontinuity within the limited Wittenoom area is real.

Figure 45 (opposite)

Phosphate distribution in parts of the Dales Gorge Member, Hole 47 at Wittenoom

Column 7. BIF 11. The complex structure at 120 cm is portion of a macule (a nodule-like thickening of a group of mesobands).

Column 8. 92–144·7 cm S12.
144·7 cm to top BIF 12.

Column 11. BIF 12. Note that the complex fine lensing between 50 and 55 cm is perfectly mirrored in the phosphate print.

Column 13. 42–104·3 cm BIF 12.
104·3 cm to top S13.

This part of S13 is fragmented and the embedding cement is reflected in the phosphate print as phosphate-free markings.

Column 19. 0–3 cm BIF 13.
3–98 cm S14.
98 cm to top BIF 14.

Column 22. 0–146 cm BIF 14.
146 cm to top S15.

S15 appears to be almost free of phosphate judging from the virtually blank print. Compare this with S13 which shows a diffuse distribution but without significant phosphate banding.

The P-band and mesoband correlation between a short length of core from Hole JG2 at Junction Gorge and the type section of the Dales Gorge Member (Hole 47A at Wittenoom) appear in Figure 47, A. Attention is directed especially to the reversal of the phosphate content of certain indisputably correlative mesobands: that is, P-bands in one core are matched almost exactly by phosphate-poor bands in the other, and *vice versa.*

Further correlations were attempted using material from which Figure 15 of Trendall and Blockley (1970) was prepared to illustrate fine-scale long-distance stratigraphic correlation. These prints, together with a reproduction of Trendall and Blockley's Figure 15, are shown in Figure 48. Though the rocks from which these prints were prepared are, with the exception of the core sample, somewhat weathered, the results suggest that while some correlation may be inferred for C and D, which are 30.6 km apart, there is none between A, B and D, which form a triangle with sides 148, 233 and 298 km in length, despite the excellent lithological correspondence at the microband level.

The limited evidence of this study suggests that the present lateral distribution of phosphate within specific horizons is either discontinuous or a localized feature. Nevertheless it is possible, indeed probable, that some basin-wide correlations could be made, particularly for sequences such as those present in column 34.

PHOSPHATE DISTRIBUTION IN S MACROBANDS

Two general conclusions may be drawn from the stain prints of S macrobands shown in Figures 44 and 45. Firstly, where marked P-banding is present within S macrobands it has no distinguishing characters from that of BIF macrobands. Secondly, lithologically uniform shale seldom shows P-banding; S15, for example, shows an almost blank print. The short length of Whaleback Shale in the panel is similar to S macrobands of the Dales Gorge Member, such as S5, S14, and S16, which are P-banded like BIF.

DISCUSSION

Two contrasted explanations are available for the phosphate distribution illustrated:

(1) Deposition of phosphate takes place on a basin-wide scale conforming to the regular precipitation of the matrix and possibly connected with the same cyclic phenomenon, but it is subsequently redistributed by local conditions during and/or after consolidation.

(2) The phosphate is deposited independently of the matrix, controlled by local variations of the phosphate content of the water of the basin, and though modified by later processes remains essentially within the original horizons.

An association of apatite-rich bands with hematite is perhaps consistent with the observation of Bonatti and others (1971) that phosphorus concentrates within the oxidized top layers of sediments. However, this is a minor feature and limited to very narrow bands. The possibility of a reducing atmosphere (Cloud, 1968) and the rapid rate of sedimentation would probably limit this process. The remainder of this discussion is concerned mainly with the second explanation.

Part of column 1 (Fig. 46, D) represents one of the more complicated segments of the short length of core examined with the electron microprobe. The results for this zone made little sense until the phosphate print was available, since in terms of the probe beam diameter the individual apatites are far apart, despite the apparent overall continuity shown in the illustration. Other similarly contorted, as well as regular patterns are also illustrated in Figures 44, 45 and 46, and are quite typical of the much greater length of tested core.

The significance of all these patterns is in the evident close relationship of phosphate to the individual sedimentary layers. If it is argued that the phosphate banding is the result of preferential concentration during consolidation and compaction then an answer is required as to why one mesoband should contain apatite while a few centimetres higher or lower in the sequence the phosphate prefers a different host. In fact, it seems likely, though more checking is required, that at one place or another every major mesoband variety will show a complete range of phosphate concentration.

It could still be argued that the phosphate was uniformly precipitated with the matrix material, or as a cyclic phenomenon within specific mesoband types, and that the present distribution reflects a physical property of the host, porosity for example, or a combination of unknown factors. But examination of prints from breccia and slump zones (Fig. 46, C for example) shows that apatite banding follows the contortions and fragmentation with considerable precision. Why has the phosphate not diffused throughout these zones? If these were isolated cases then one could suggest special conditions, but it is clear that wherever phosphate is present in contorted, brecciated or podded zones, the distribution is demonstrably controlled by the original bedding, despite the variety of processes to which the laminations have been subjected.

Migration of phosphate could still account for anomalies such as those in the matching cores from Junction Gorge and the type section, particularly in zones where skeletal apatites and other "late" crystallizing forms are present. The high lateral permeability as opposed to the low vertical permeability of BIF (Dr. T. Parks, CSIRO, pers. comm.) could act as a control for some of the banding, though vertical mobility seems highly unlikely in view of the very marked separation of closely spaced bands throughout the long lengths of phosphate prints available. However, Figure 47, B is an example of a stylolitic contact which fortuitously cuts into a phosphate band. Here we see two different rock types in lateral continuity in a structure formed by a process which assumes solution effects, and yet there is no indication of cross migration of phosphate.

If such a lateral migration does occur then it must be a highly selective process and we are left with the fundamental problem of explaining how such fine details as "phosphate microbanding" can be preserved and why intraformational brecciation and slumping patterns can still be mirrored in the prints without significant signs of diffusion, not just occasionally, but as a general feature of the sediments.

Thus the writer is drawn to the conclusion that the P-banding of these sediments is essentially a primary depositional feature, modified only in a minor way by later processes, chiefly compaction and recrystallization.

To sum up, although there is strong evidence of lateral correlation over a few kilometres for many P-bands there are also many anomalies which are accentuated with distance. Cyclic depostion is convincingly demonstrated for at least one cyclothem sequence, and it would be strange in view of the remarkable stratigraphic correlations across the sediments, if at least some basin-wide phosphate correlations could not be made. On the other hand no evidence has yet been found to suggest that within the Dales Gorge Member, a correlation exists between phosphate and specific lithological types even within the regular cyclothem sequences. The evidence of the phosphate prints suggests that the P-bands reflect a primary depositional control and that they are either laterally discontinuous or more likely, a localized depositional feature.

A SUGGESTED DEPOSITIONAL ORIGIN FOR PHOSPHATE DISTRIBUTION

It has been argued that the phosphate bands reflect a primary depositional control. Any genetic process therefore must explain both erratic and cyclic deposition, and at the same time retain some consistency with the apparently unrelated systematic basin-wide deposition of the sediments.

To do so I suggest, that in general, phosphate influx into the basin was erratic, probably related to volcanism and differentiation, and perhaps also to temporary openings of the basin to the sea. To some extent the fumarolic activity suggested by Trendall and Blockley (1970) should produce local concentrations of the various constituents in the basin waters. By itself, such a control for local phosphate deposition would imply a similar concentration of other components, and also that the concentration should be restricted to centres of volcanic activity. This is contrary to the evidence of the basin-wide lithological correlations. However if as a result of these temporary concentrations, there was a rapid build up of phosphate-fixing organisms, (analogous to the proliferation of blue-green algae blooms in polluted waters such as Lake Michigan), this might lead to a local phosphate accumulation that did not necessarily have a genetic relationship to the particular matrix being co-precipitated but was nevertheless controlled to some extent by the same general mechanism.* With continued phosphate influx these blooms might extend farther from the source, or as with the other components be dispersed through the basin by currents.

If this idea is acceptable it could be logically extended to multiple volcanic sources of the same type, each producing a varying output as differentiation proceeded. It is not hard to imagine this as a series of unrelated ripples in a pond, interacting to produce highs and lows at different places, and it would not be unreasonable to expect periods of general uniformity consistent with the cyclic patterns such as in column 34. The fine "phosphate microbanding" suggests that a seasonal control was superimposed on the general process, but the hypothesis does not exclude the possibility of direct inorganic precipitation or phosphate exchange between water and carbonate. All three processes acting in concert or separately might have operated to nucleate the variety of apatite forms seen in the sediments. For example, one process may have resulted in the formation of ferrous phosphate such as vivianite, which were subsequently oxidized to give the globular and cigar

* Trendall and Blockley (1970) suggest an algal mat over the basin acting as a buffer between spasmodic influx of matrix components and the regular deposition of BIF.

Figure 46 (opposite)

Photographs of Brockman Iron Formantion drill core, with stratigraphically equivalent phosphate stain prints

A Column 34. Part of BIF 16. Cyclic deposition of phosphate related to the Calamina cyclothem. Trendall and Blockley (1970) suggest a deposition rate of between 1,000 and 3,000 years for each cycle ; thus this portion of the column represents a suggested time span of between 9,000 and 27,000 years. The apparently rich phosphate bands at 95 cm are the result of excessive reagent in the strip during printing.

B Column 42. Joffre Member. This column is fairly typical of the approximately 21 m of Joffre Member core in the exhibit, and shows the dominance of sharply marked phosphate bands in a background of very low phosphate. This distribution is in marked contrast to the very varied Dales Gorge Member prints.

C Junction Gorge core. Dales Gorge Member, BIF 4, equivalent to approximately 40 m on the type section. The print was prepared from the curved and porous surface of untreated core, but though it lacks the clarity of previous prints shows the phosphate mirroring the contortions and fragmentation in podded and brecciated zones.

D Part of Column 1 (see Fig. 44). A half-scale reproduction of part of the core used for electron probe studies. The print illustrates the retention of phosphate within the original sedimentary layers, despite the complex post-depositional changes that have produced this podded zone. It should be noted that phosphate and podding are not necessarily associated ; see for example, Fig. 45 Column 22, 130 cm.

Figure 47 (over)

Photographs of Brockman Iron Formation drill core, with stratigraphically equivalent phosphate stain prints

A Lateral correlation of phosphate banding. The two groups of four strips represent, from left to right—phosphate print, Junction Gorge core, type section core, phosphate print, respectively. The matching cores are from the Dales Gorge Member BIF 13 and are marked at 343 feet (104·55 m) and 340 feet (103·63 m) of the type section respectively. The phosphate prints were prepared from the untreated porous surface of the core and show blemishes unrelated to the actual phosphate distribution. The two cores are 80 km apart but show excellent mesoband correspondence at this level. The phosphate distribution however does not show this correspondence and in fact shows many horizons where the distribution is completely reversed. The Junction Gorge core generally shows phosphate in the lighter coloured zones, and though the type section is less regular it is the darker zones that are generally phosphate bearing.

B Part of an S macroband of the Dales Gorge Member. The structure in the centre of the figure is interpreted as a stylolitic contact cutting into a phosphate band. The absence of diffusion of phosphate across the boundary of laterally adjacent sediments indicates the postdepositional immobility of phosphate.

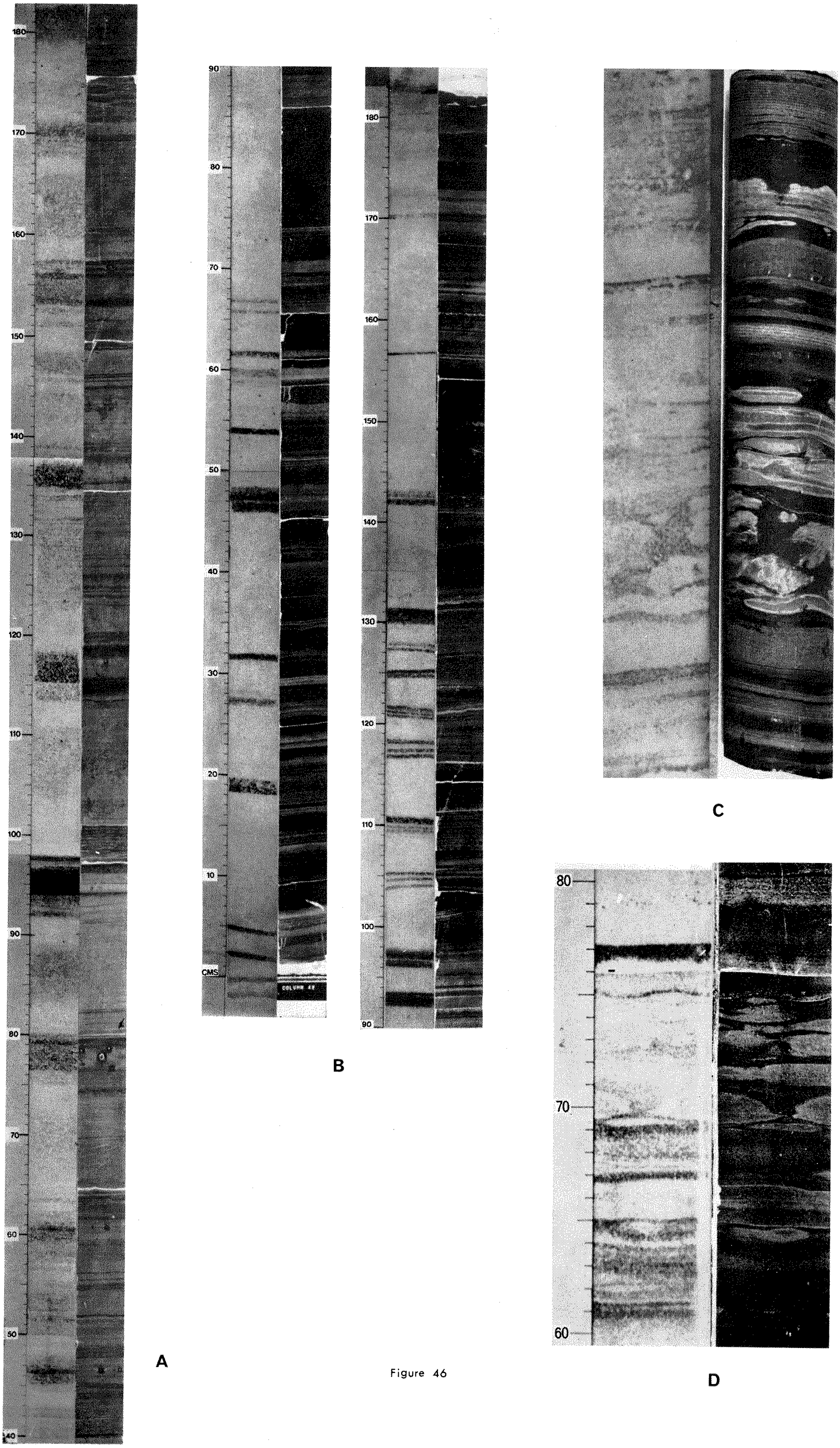
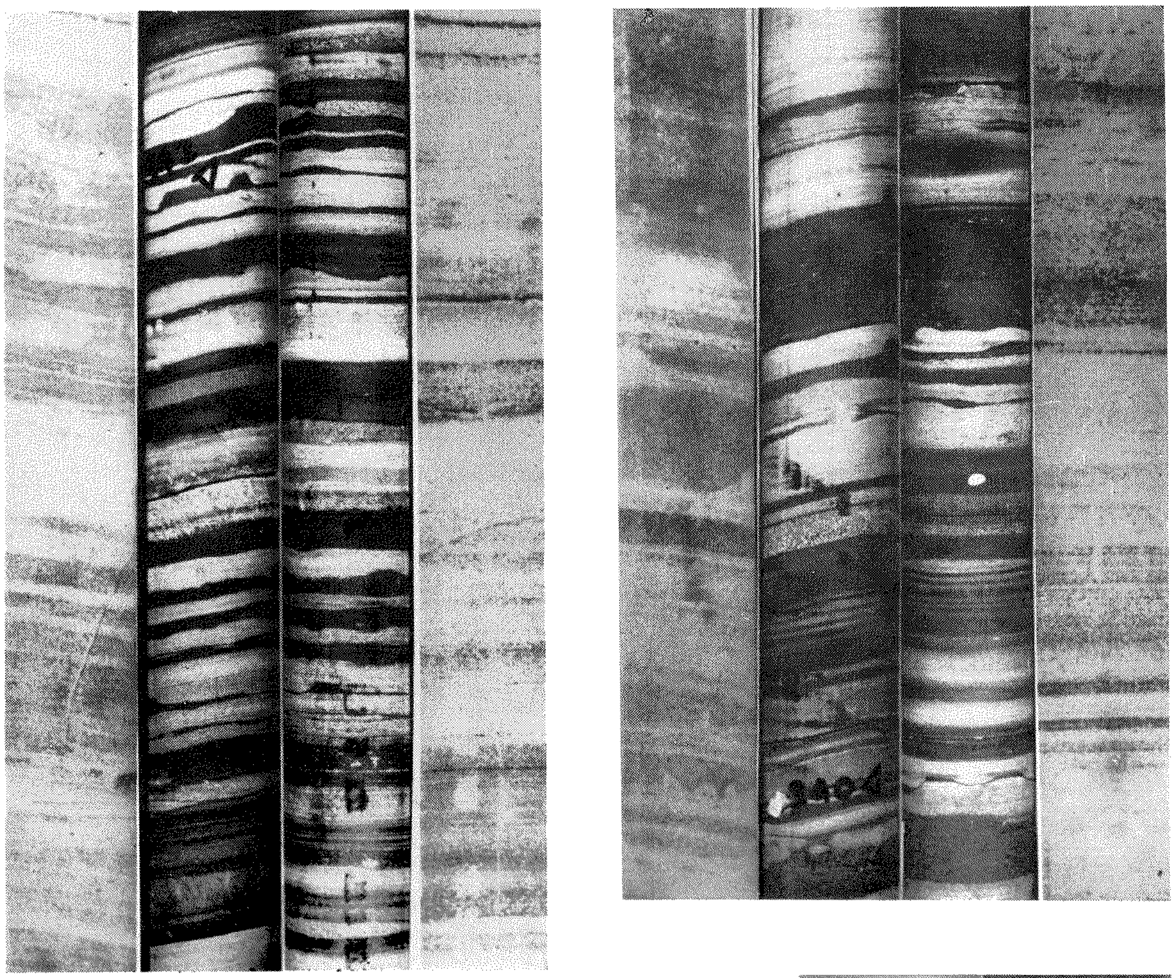


Figure 46



A

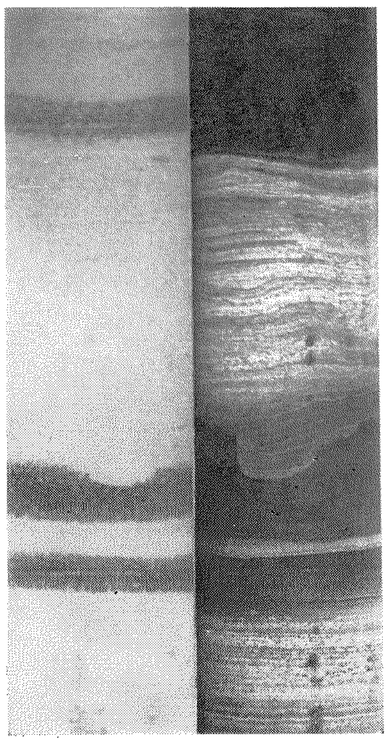


Figure 47

B

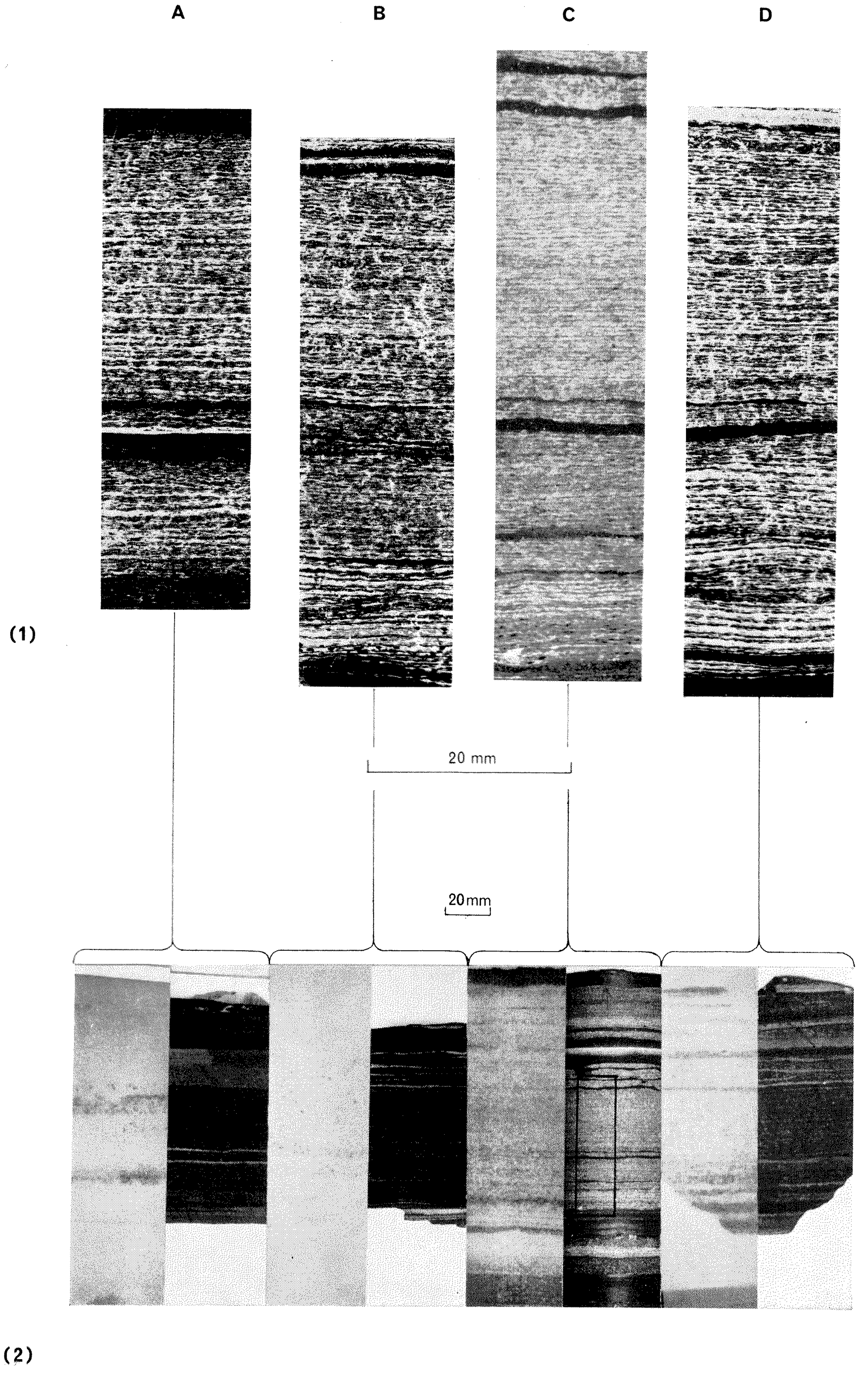


Figure 48

forms (Fig. 35 of Trendal and Blockley, 1970) with the iron trapped as fine oxide inclusions. Localized recrystallization of phosphate, either together with the matrix minerals or slightly later, could explain the interstitial nature of the skeletal and prismatic apatites, but the minute anhedral spots included within chert and stilpnomelane grains must have been trapped before crystallization of these minerals.

It seems reasonable to suggest an organic origin for much of the phosphate in the banded iron formations, but oxygen isotope studies would clarify this (Degens, 1965). Carbon isotope studies by Becker and Clayton (1972) lead them to suggest an organic origin for much of the carbonate in the Dales Gorge Member and that during the period of formation of this member, the basin was separated from, but located near an ocean. However, they do not rule out volcanism as a source of the "light" carbon in the iron formation.

Finally, one advantage of the planktonic hypothesis is that it is not necessary to invoke new concepts. The process of phosphate induced plant growth in restricted waters, whether from hot springs or detergents, may have been as valid 2,000 million years ago as it is today.

PHOSPHORUS AND THE IRON ORE

One of the chief virtues of the phosphate printing technique is the rapidity with which long lengths of core can be tested, whether in the laboratory or the field. While it cannot, in its present form, be used to test lattice phosphorus of ores such as those described by Graham (in press), it could be readily applied to ores carrying soluble phosphate.

The technique could also be used to provide a rapid semi-quantitative estimate of phosphate in sediments around the known ore bodies, to provide a clue to the relationship between phosphorus in ore and protore.

Figure 48 (opposite)

Phosphate distribution in stratigraphically equivalent samples of the Dales Gorge Member from widely separated areas

(1) A reproduction of Figure 15, Bull. 119. Trendall and Blockley 1970. Comparison of the chert-magnetite group at about 11·15 to 11·22 m (36·6 to 36·85 ft) in the type section of the Dales Gorge Member (BIF 0) at widely separated localities.

A Thin-section from Woongarra Gorge (lat. 22° 52′ 30″ S, long. 117° 07′ 30″ E).

B Thin-section from Point James (lat. 20° 58′ S, long. 117° 07′ 30″ E).

C Surface photograph of the type section from Hole 47A at Wittenoom Gorge.

D Thin-section from Dales Gorge (lat. 22° 28′ S, long. 118° 33′ E).

The localities A, B and D form a triangle with sides of length 148, 233, and 298 km. C and D by comparison, only 30·6 km apart. The lateral correlation of internal irregularities of the microbanding below mesoband scale is evident.

(2) Specimens from which Fig. 48 (1) above prepared, together with matching phosphate prints. A, B and C are polished surfaces and the reproductions show the opaques as light coloured bands and the chert as dark bands. This is the reverse of the thin-section and core reproductions. The rectangle superimposed on C is the area represented by C of Fig. 48 (1). Some correlation of the phosphate distribution can be inferred between C and D but none is apparent between A, B and D. Part of this lack of correspondence may be due to the weathered nature of the polished samples but there are sufficient remnant features to indicate the presence of non-correlative phosphate bands.

ACKNOWLEDGMENTS

I would like to express my appreciation for the co-operation I have received during this project from colleagues in C.S.I.R.O. and from the Director and staff of the G.S.W.A. Among C.S.I.R.O. staff Dr. J. Graham and Mr. R. B. W. Vigers are thanked for help with the probe work, Mr. C. E. S. Davis for his guidance in developing the phosphate print technique and Mr. W. E. Ewers for his initiation and continued support of the project.

Special thanks are due to Mr. L. Fimmell and technical staff of the G.S.W.A. for their help in preparing the samples for study and the stain printing and photographic reproductions from over 100m of drill core. Dr. A. F. Trendall's encouragement and active assistance were essential to the project.

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THE GEOLOGY OF THE FITZGERALD RIVER LIGNITE

by A. E. Cockbain and W. J. E. van de Graaff

ABSTRACT

The area consists of a plateau dissected by the Fitzgerald and Susetta Rivers and is situated around the junction of these two rivers. Over most of the area the Eocene Plantagenet Group, consisting of the lower, lignite-bearing Werillup Formation and the upper, spongolite-bearing Pallinup Siltstone, unconformably overlies Precambrian quartzites and phyllites (Mount Barren Beds) or granite. The Pallinup Siltstone forms most of the plateau; the valleys are underlain by the Werillup Formation with a few Precambrian inliers and are floored by alluvium. Lignite lenses and flakes are present throughout the Werillup Formation and are also concentrated in a bed about 3 m thick which occurs near the junction of the Fitzgerald and Susetta Rivers. It is estimated that about 1.1 million t of lignite averaging 2.3 per cent. (dry basis, benzene extraction) montan wax is present. On a wet basis this gives a figure of about 15,000 t of montan wax occurring in the Fitzgerald River lignite. The wax has a lower melting point and higher resin content than German or Californian waxes.

INTRODUCTION

The area covered in this paper lies some 50 km east-southeast of Jerramungup and is about 520 km by road from Perth (Fig. 49). It includes part of the Fitzgerald River and its tributaries the Susetta River, Twertup Creek and Tooartup Creek. Geologically it is part of the Bremer Basin.

This study was undertaken because of proposals to explore for and mine lignite occurring in the area for its extractable montan wax. As the area of interest is situated in a flora and fauna reserve the question of mining and exploration was referred to the Environmental Protection Authority This paper is a summary of work done at the request of the Environmental Protection Authority and gives an account of the geology of the Fitzgerald River lignite.

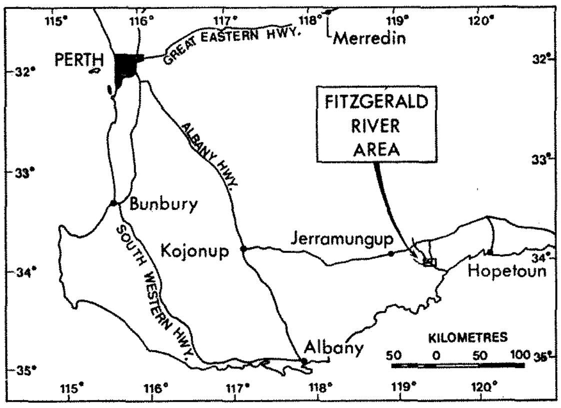

Figure 49. Fitzgerald River area—locality map.

PREVIOUS WORK

Lignite was first discovered in the Fitzgerald River area by the Surveyor-General, J. S. Roe, in 1848 (Roe, 1852). The lignite was described as containing elongated globules of bitumen ". . . from the size of a pea to that of a goose egg . . ." (Roe, 1852, p. 36). The lignite bed was horizontal but the adjoining shales were reported to have a dip of 45°. Roe also recorded that according to a local Aboriginal, a French ship had refuelled from coal occurring in the Fitzgerald Inlet. He was of the opinion that the deposit would be a valuable source of fuel for the colony. Gregory (1861) discussed the lignite under the heading "Carboniferous Rocks" and stated that the bed is horizontal ". . . resting unconformably upon the edges of highly elevated Carboniferous shales, and contains many distinct fragments of only semi-fossilized wood and pieces of infusable resin . . ." (Gregory, 1861, p. 480).

Both Roe and Gregory persisted in calling the lignite "coal" and tacitly assumed that it was Carboniferous in age. However, Dixon (1884) recognized that ". . . the supposed coal was nothing but a few very thin beds of brown lignite . . ." (Dixon, 1884, p. 9) and was probably of the same age as the sandstones through which the Fitzgerald River flowed. He also noted that the lignite rested on " . . . metamorphic sandstones, jaspers and micaceous schists . . ." and not on Carboniferous shales as Gregory thought. Nicolay (1876, 1886) could find no indications of Carboniferous rocks and stated that there was no coal present in the area, but only a deposit 1.5 m thick "... of a mineral termed by the French 'turba' . . ." (Nicolay, 1886, p. 7) by which he presumably meant peat.

Woodward (1890) examined the area and considered the lignite " . . . to be nothing more than a brown carbonaceous substance, containing a certain amount of asphaltum . . . it is not a coal, and will never be of any commercial value as a fuel", (Woodward, 1890, p. 50). He recognized that the deposits occur in hollows on the upturned edges of altered slates and quartz reefs.

No further geological work was done in the area until 1921 when an exploratory well (herein named Jonacoonack No. 1) was drilled for petroleum. Jonacoonack No. 1 was drilled to a depth of 108 m through Precambrian quartzites and phyllites of the Mount Barren Beds (see Maitland, 1922, and appendices therein for details). A brief summary of the lignite occurrence in the Fitzgerald River area was given by Maitland (1922) who reported that two bores had been drilled in the area " . . . one is said to be 216 and the other 397 feet deep. These are stated to have passed through two seams of lignite 16 and 18 feet in thickness. The site, however, of only one of the bores in question has been located on a plan and there is neither record nor samples available of the rocks pierced" (Maitland, 1922, p. 14). Simpson (in Maitland, 1922) established that the rounded nodules (Roe's globules) were not bituminous, but a resin of vegetable origin.

In 1928, interest in the lignite was revived, mainly as a source of crude oil by destructive distillation (Blatchford, 1929). Wheeler's Shaft, on the Fitzgerald River, and a bore 1.5 km downstream, were sited on or near lignite outcrops and penetrated 2.9 m and 2.4 m of lignite respectively. A second bore some 300 m up the Susetta River was not near any known outcrop and was reported as failing to reach the lignite. Blatchford gave analyses of the lignite and produced a map showing the position of two bores labelled "Dunstan's Bore" and "Old Bore" which are presumably the bores referred to by Maitland in 1922. In addition, Blatchford reported the presence of blocks of lignite upstream from the drilled area near the junction of the Fitzgerald River and Twertup Creek. He concluded that there was ". . . an extensive deposit of brown coal, more or less proved . . ." (Blatchford, 1929, p. 6).

Later Blatchford (1930) referred to the lignite-bearing beds as the "Fitzgerald Brown Coal Series" and assigned them to the Miocene. Cockbain (1968) recommended the abandonment of this name on the grounds that it was never adequately defined; he placed the lignite in the Werillup Formation of the Plantagenet Group, which is of Eocene age. He also gave a summary of work on the Phanerozoic sediments of the Bremer Basin ("Denmark-Esperance region" of his paper) and formalized the stratigraphic nomenclature of the Plantagenet Group.

METHODS OF STUDY

The present study commenced with a field reconnaissance of the area made from the 6th to 11th September, 1972. A preliminary report and a geological map on a scale of 1 : 30,000 were prepared as a result of this work (Geological Survey File 181/63) and a drilling programme was recommended. The drilling programme was to consist initially of 12 holes (later increased to 15), and if this indicated that the lignite was widespread it was to be followed by a second-stage programme with a network of holes.

The drilling started on 13th November and was completed on 30th November. A gemcodril 210B auger drill with a wireline coring device was used. A total of 261.4 m of hole was drilled and 74 cores were cut. Of the 15 holes, three were drilled twice and two were drilled three times because of either drilling difficulties or non-recovery of core in vital parts of the Werillup Formation. The position and elevation of all drillholes were surveyed by means of a plane table and telescopic alidade. Datum for the elevations is ground level at the easternmost lignite outcrop in the area which occurs in the bed of the Fitzgerald River east of drillhole N.

GEOMORPHOLOGY

The Fitzgerald River area (Fig. 50) consists of a plateau dissected by broad river valleys which have steep sides and gently sloping floors. The plateau is about 150 m above sea level and is underlain by Tertiary (Eocene) sediments. The present-day river channels have cut down into the broad valley floors, which are underlain mainly by alluvium through which a few buried mounds of Precambrian rocks appear. The scarps at the edges of the valleys are up to 50m high. There are indications in places, for example on the west side of the Fitzgerald River north of the junction with Twertup Creek, of at least three sets of river terraces. In and beyond the southeast part of the area the Fitzgerald River cuts through Precambrian rocks and there is no extensive alluvial cover.

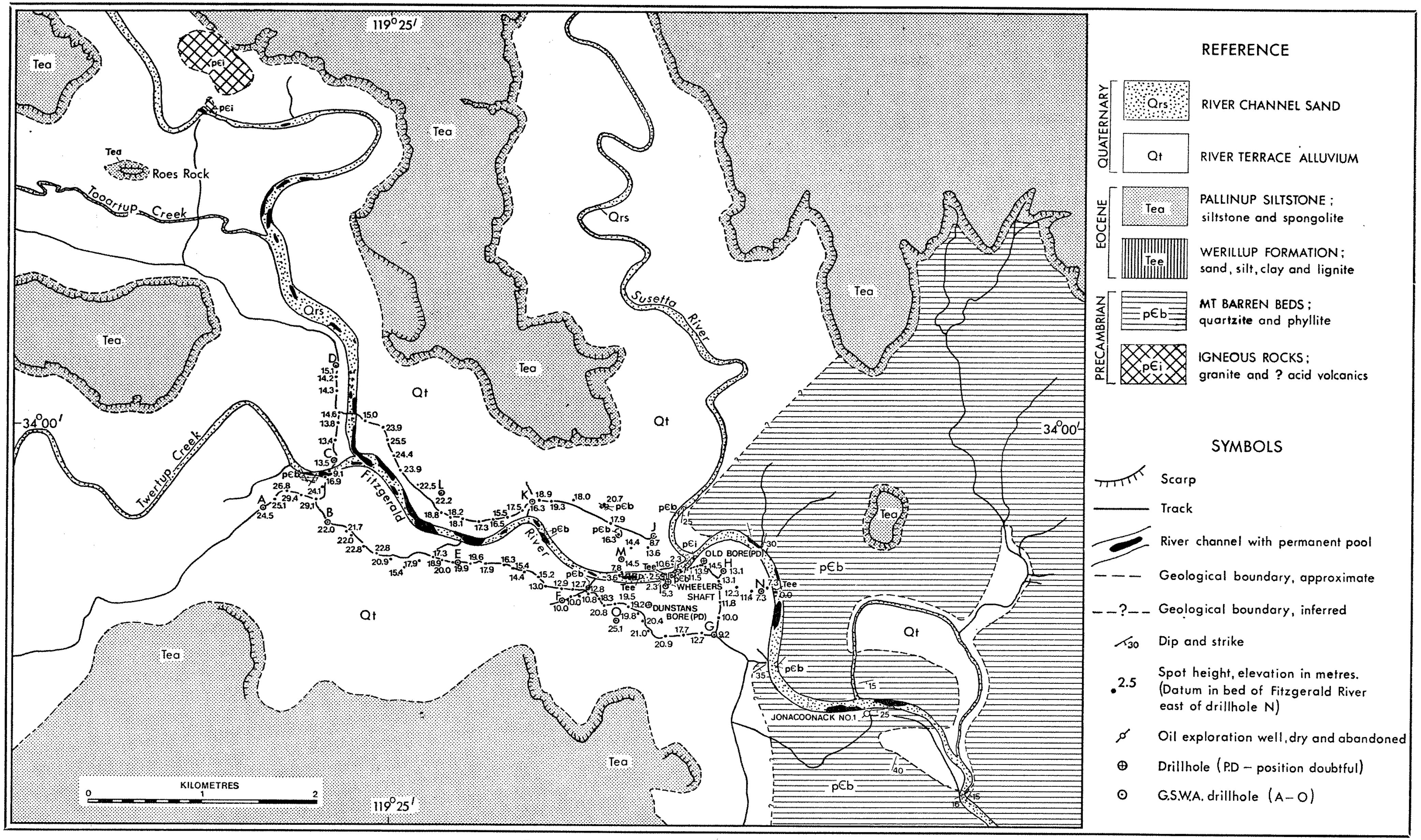

Figure 50. Geological map—Fitzgerald River area.

GEOLOGY

The stratigraphic succession in the Fitzgerald River area is as follows:

Quaternary	River-channel sands River-terrace alluvium	— — — — —	at least 12·5 m thick
Plantagenet Group	Pallinup Siltstone	....	up to 60 m thick
	Werillup Formation	—	at least 24 m thick
Precambrian	Mount Barren Beds Granite	— — — —	thickness unknown

Figure 50 is a geological map of the area, and also shows the position of the drillholes and some elevation data. Geological logs of the drillholes are on file at the Geological Survey and are summarized in Table 23 and Figure 51. Cross-sections in the form of a fence diagram are presented in Figure 52.

TABLE 23. SUMMARY OF DRILLHOLE DATA

Drillhole	A		B		C		D		E		F		G		H	
Ground Elevation (see text for datum)	24·5		22·0		13·5		15·1		19·9		10·0		9·2		13·1	
Formation (formation tops below R.T. and relative to datum)	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum
Alluvium	0·5	24·5	0·5	22·0	0·5	13·5	0·5	15·1	0·5	19·9	0·5	10·0	0·5	9·2	0·5	13·1
Pallinup Siltstone	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Werillup Formation	....	....	....	....	....	....	....	....	5·5	14·9	1·1	9·4	5·1	4·6	8·5	5·1
Precambrian	8·5	16·5	4·6	17·8	12·0	2·0	9·1	6·5	....	....	18·6	—8·2	8·6	1·1	13·0	0·6
T.D.	12·1	12·9	7·5	15·0	12·5	1·5	13·6	2·0	28·8	—8·4	21·0	—10·5	9·0	0·7	18·9	—5·3

Drillhole	I		J		K		L		M		N		O	
Ground Elevation (see text for datum)	5·3		8·7		16·3		22·2		14·5		7·3		25·1	
Formation (formation tops below R.T. and relative to datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum	R.T.	Datum
Alluvium	0·5	5·3	0·5	8·7	0·5	16·3	0·5	22·2	0·5	14·5	0·5	7·3	0·5	25·1
Pallinup Siltstone	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Werillup Formation	3·5	2·3	....	....	4·4	12·4	11·3	11·4	11·7	3·3	6·3	1·5	12·6	13·0
Precambrian	17·1	—11·3	2·1	7·1	28·5	—11·7	30·6	—7·9	20·0	—5·0	20·0	—12·2	14·1	11·5
T.D.	17·5	—11·7	2·9	6·3	29·0	—12·2	31·3	—8·6	21·8	—6·8	21·2	—13·4	14·3	11·3

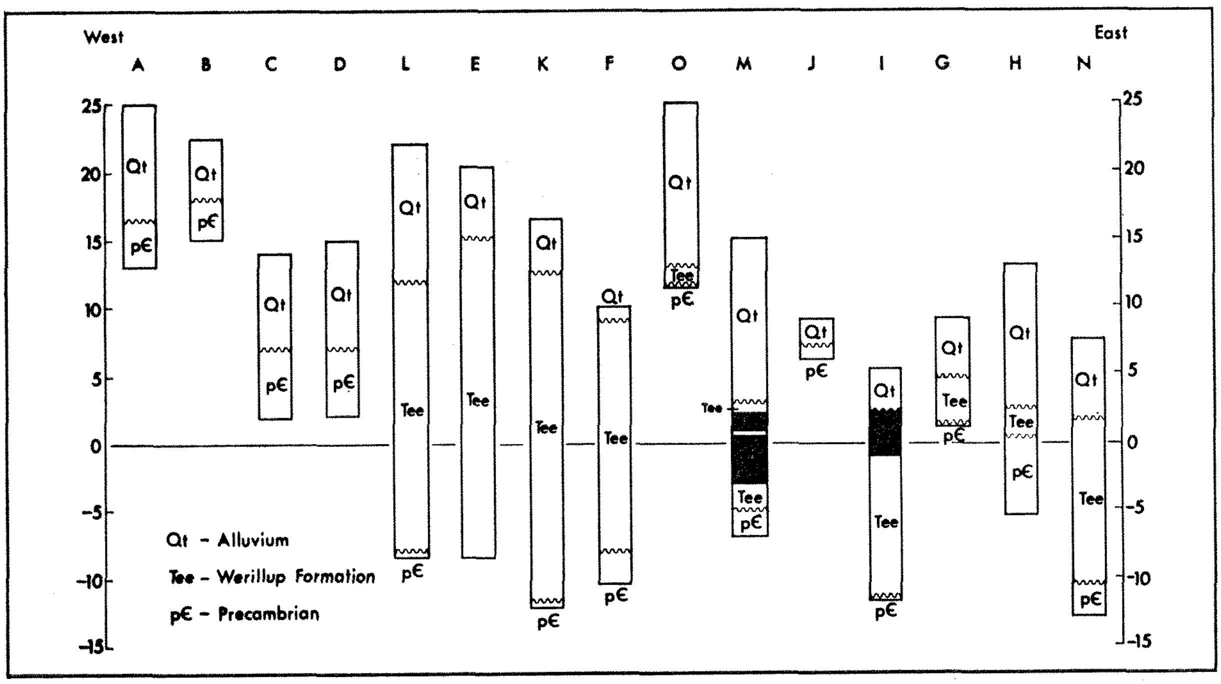

Figure 51. Stratigraphic correlation of drillholes and distribution of lignite (in black). Elevations are relative to datum in bed of Fitzgerald River east of drillhole N.

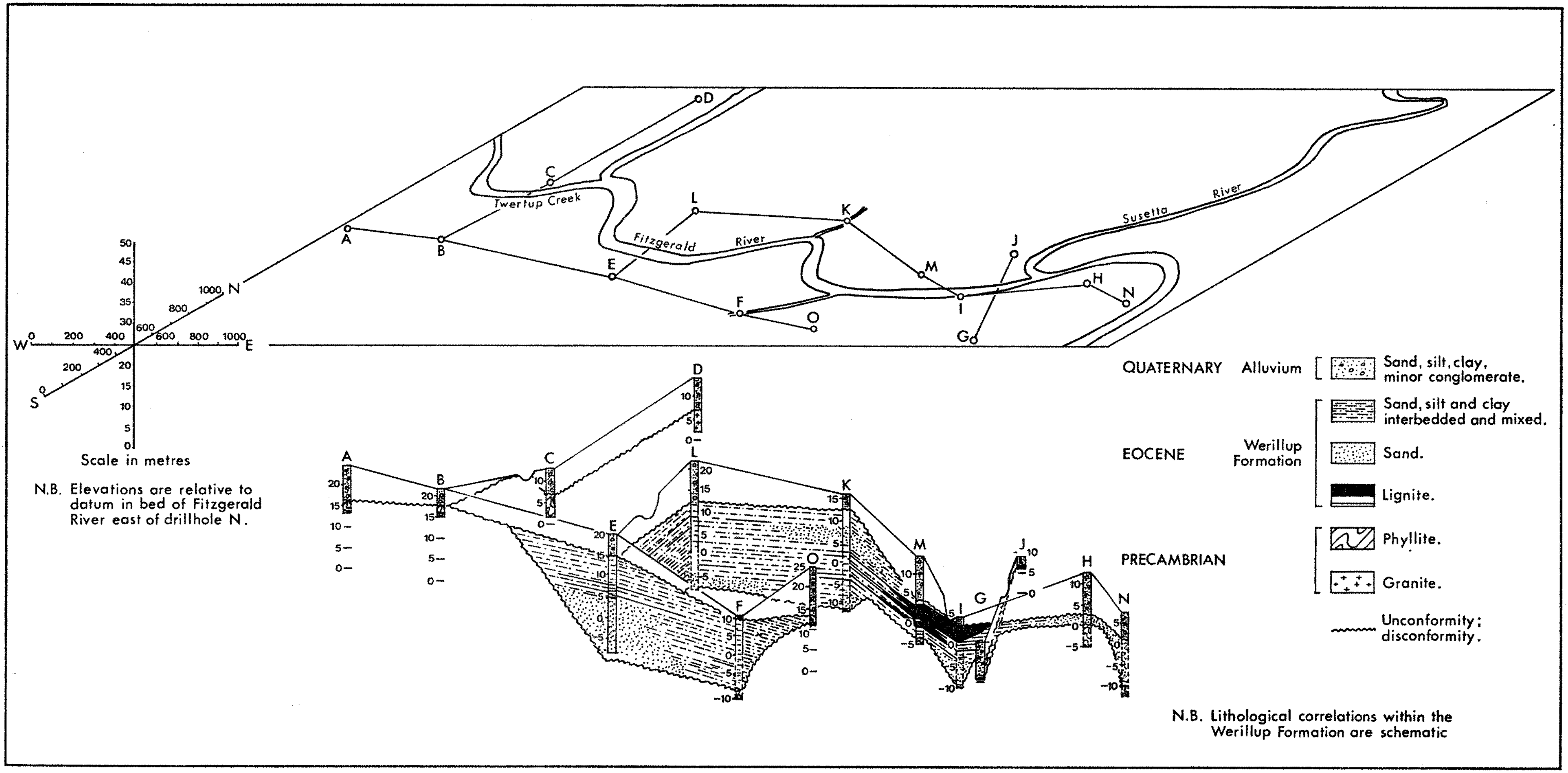

Figure 52. Fence diagram showing correlation of drillholes.

PRECAMBRIAN ROCKS

The Precambrian rocks consist mainly of granite in the north and quartzites and phyllites of the Mount Barren Beds in the south. The relationship between the two Precambrian units cannot be determined in the area studied; the Mount Barren Beds are considered to be Proterozic in age and the granite is presumed to be of Archaean age.

The granite has been examined only in the area north of Roes Rock where it is coarse grained, contains a few clots of mafic minerals, is slightly banded, but is otherwise structureless. Weathered granitic material was encountered at the base of drillhole D and granite must extend at least this far south.

The Mount Barren Beds are the basement rocks over most of the Fitzgerald River area. They consist of pale grey to green phyllites, which are often soapy to the touch, and subordinate white quartzite beds. Both dip and strike are variable, but the beds usually dip in a general southeasterly direction at 15 to 40°. The Mount Barren Beds occur in scattered outcrops along the Fitzgerald and Susetta river valleys; the best exposures are along the Fitzgerald River in the vicinity of Jonacoonack No. 1 well. The formation was encountered in all drillholes except D and E. Drillhole E did not reach basement and D encountered weathered granite. Drillhole H bottomed in phyllite with minor intercalations of an igneous rock similar to that occurring in the adjacent Fitzgerald River. This igneous rock has been identified as an acid volcanic rock (J. D. Lewis, 1972, pers. comm.); the relationship of these volcanic rocks with the Mount Barren Beds is uncertain.

PLANTAGENT GROUP

The Plantagenet Group consists of a lower dark coloured lignite-bearing unit, the Werillup Formation, and an upper light coloured, spongolite-bearing unit, the Pallinup Siltstone (Cockbain, 1968).

The group is horizontal and rests on a basement surface of considerable relief. North of Roes Rock a hill of granite rises 50 m above river level, while some 6 km to the southeast basement is encountered about 13 m below datum level in drillhole I; taking into account the gradient of the river this gives a relief on the basement surface of about 80 m in the area mapped. Figure 51 gives an idea of the iregularity of the basement surface in the area drilled. The Werillup Formation occupies hollows in the basement surface and is overlapped by the Pallinup Siltstone which then rests directly on basement, for example around the granite hills north of Roes Rock.

Werillup Formation

The Werillup Formation consists of dark brown to black clay, loose sand to friable sandstone (occasionally pyritic) and lignite. The formation crops out in only two places: (a) upstream from the junction of the Fitzgerald and Susetta Rivers and (b) 1.5 km downstream from the junction of these two rivers.

Outcrop (a) is the lignite exposure near which Wheeler's Shaft was sunk in 1928. Here the lignite is black to dark brown with recognizable plant remains (mainly stems) and little terrigenous material; it has an exposed thickness of about 1 m and forms a small waterfall. Blatchford (1929) recorded 2.9 m of lignite in Wheeler's Shaft and the nearby drillholes I and M penetrated 3 m and about 4 m of lignite respectively. Upstream from the waterfall the lignite can be traced for about 200 m, but is discontinuously exposed beneath river-channel sands; the amount of lignite exposed depending on the amount of sand removed by river floods. Present exposures are more extensive than those of recent years (M. Foggarty, 1972, pers. comm.). The outcrop extends downstream for about 75 m and in this distance passes laterally into dark brown clay and sand with lignitic interbeds. Outcrop (b) is probably the original outcrop discovered by Roe in 1848. It consists of black to dark brown brittle impure lignite with quartz grains up to 1 cm in diameter, and occurs in the river bed. According to Blatchford (1929) a bore drilled near here penetrated 2.4 m of lignite.

The Werillup Formation was encountered in all drillholes except A, B, C, D, and J, and is restricted to the valley of the Fitzgerald River between its confluence with the Twertup and the Susetta (Fig 53). Blatchford's (1929) report of lignite blocks at the junction of the Fitzgerald

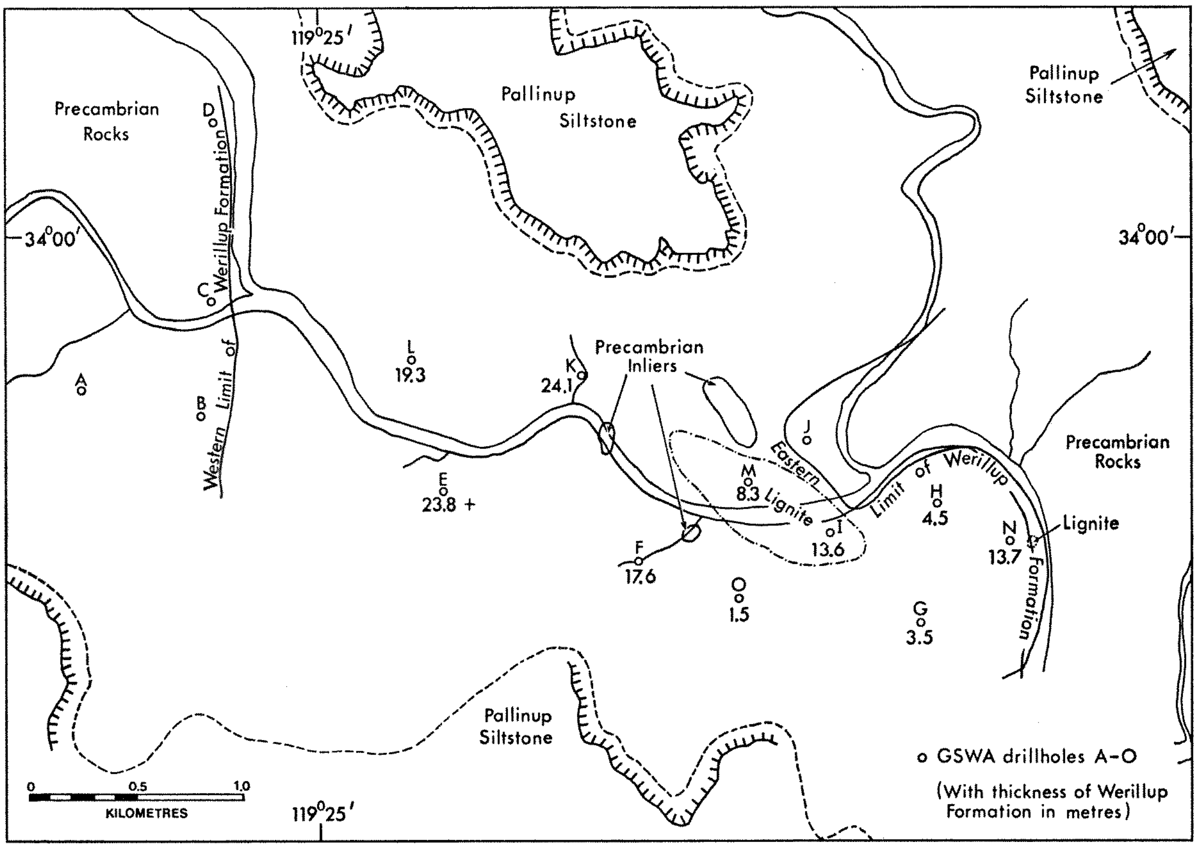

Figure 53. Areal extent of Werillup Formation beneath river-terrace alluvium.

River and Twertup Creek was not confirmed. The formation has a maximum known thickness in the area of 24.1 m (in drillhole K) but shows rapid changes in thickness over a short distance (see Figs. 51 and 52). Only two drillholes, I and M, penetrated a bed of lignite of more than a few centimetres thickness; the remaining eight drillholes in the Werillup Formation went through a sequence of dark coloured sand and clay with or without minor lignite lenses and flakes (Figs. 51 and 52). Lithologically the formation varies both laterally and vertically as can be seen from Figure 52. However, there appears to be a general sequence of sandy beds at the base followed by clayey strata. Lignite is developed within the clays, and the drillholes show that only one lignite bed is present in the area, at about river level, and that the bed does not extend far beyond the known outcrop.

The Werillup Formation is of Late Eocene age (Cockbain, 1968). In the Fitzgerald River area palynological work (Appendix 2) cannot date the formation more precisely than Early Tertiary.

Pallinup Siltstone

The Pallinup Siltstone consists of pale brown to creamy white siltstone and spongolite. The unit forms spectacular mesa topography, well exemplified by Roes Rock, but is not present in the floor of the river valleys and was not encountered in any of the drillholes. The maximum thickness of the Pallinup Siltstone in the area mapped is of the order of 60 m. Cockbain (1968) gives further details of the formation.

RIVER-TERRACE ALLUVIUM

River-terrace alluvium, arbitrarily assigned to the Quaternary, underlies most of the floor of the river valleys and was penetrated in all the drillholes. The unit consists of light grey, poorly sorted sand and clay with pebbles of quartzite and spongolite. In places, particularly at the edge of small stream channels, the alluvium is indurated and ferruginized; this induration is very local in distribution and was only encountered in two drillholes, J and N.

The alluvium rests on an uneven erosion surface which cuts across the underlying formations. The elevation of this surface ranges in the drill-holes from +18 m (in D) to +1.6 m (in N) (Fig. 51). Erosion has cut into the upper part of the Werillup Formation, and at drillhole I and adjacent outcrops in the bed of the Fitzgerald River it can be shown that the top of the lignite has been eroded away. The maximum measured thickness of alluvium is in drillhole O, where 12.5 m was penetrated.

The alluvium was formed by the rivers in the area dumping their sedimentary load and building up the valley floor. This must have occurred during a period of greater rainfall than at present and after a time of vigorous erosion which produced the broad valleys cut through the plateau of Plantagenet Group sediments. At least three different river-terrace levels occur in the area; no attempt has been made to map these terraces, but they must indicate a fairly complex Quaternary history for the area.

RIVER-CHANNEL SANDS

The present day river channel is cut into the alluvium and is floored by outcrops of pre-Quaternary rock units and by Recent river-channel sand. This sand is reworked alluvium and its distribution changes from time to time and is controlled by the infrequent river floods.

DISTRIBUTION OF LIGNITE

The lignite occurs in the Werillup Formation, and its distribution is consequently determined by the areal extent of that formation. However, three other factors also affect the distribution of the lignite (Fig. 54):

(1) Lateral facies change within the Werillup Formation. Only one bed of lignite, present near the top of the Werillup Formation, occurs in the Fitzgerald River area. Both drilling and examination of outcrops show that the bed is restricted in its areal extent and passes laterally into sand and clay with lignite fragments.

(2) Uneven basement surface. The Werillup Formation was laid down on an uneven basement surface and occupies hollows in this surface. In places, for example 100 m downstream from Wheeler's Shaft, basement rock crops out at or above the elevation of the lignite bed.

(3) Erosion surface at base of alluvium. Erosion has cut down into the upper part of the Werillup Formation and removed the top of the lignite bed in the vicinity of drill-hole I.

The area underlain by the Werillup Formation, as determined by field mapping and drilling, is shown in Figure 53. Lignite is present in only the eastern portion of this area and is centred around the known outcrops. The lignite encountered in drillholes I and M forms part of the larger of the two occurrences; the boundary of this occurrence has been drawn using both drillhole and outcrop evidence. The other lignite occurrence, east of drillhole N, is based on the outcrop in the river bed and Blatchford's (1929) statement that the bed is 2.4 m thick in a bore near here. However, the field relationships and drilling, especially drillholes H and N, show that the occurrence must be very small.

The overburden ration in drillhole M is about 1 : 4. Obviously this ratio will increase towards the edge of the area underlain by lignite due to thinning of the lignite bed, and will be lowest in the river bed where the lignite crops out.

It is suggested that in the Fitzgerald River area the Werillup Formation was laid down in a small basin roughly co-extensive with the area shown in Figure 53. Sand and clay were brought into the basin by a river flowing from the west. Swamp conditions were established, and peat accumulated in the downstream part of the basin; upstream the river built up a sandy delta. The basin may have been near sea level as some of the sands show marine influence. The result of this pattern of conditions was to produce a fluviatile-lacustrine deposit with sand and clay in the upstream (western) part and sand, clay and lignite downstream (to the east). If this picture is correct it implies that

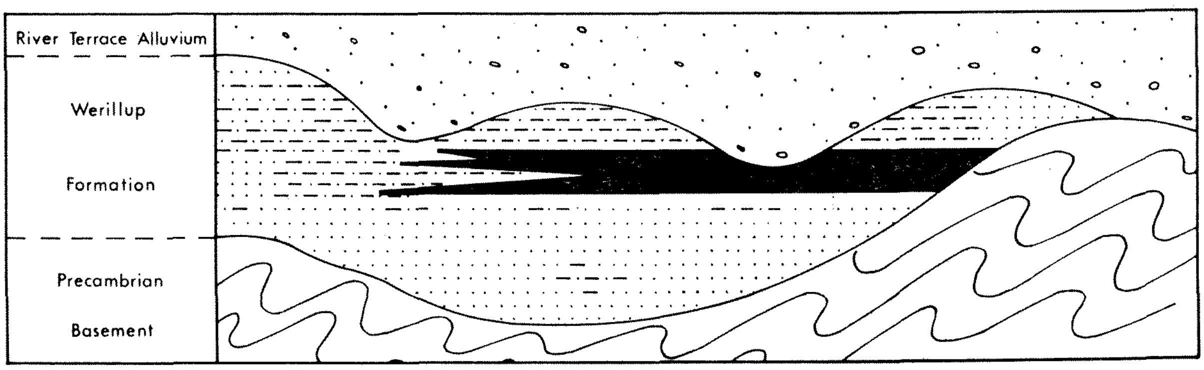

Figure 54. Diagram showing factors affecting distribution of lignite (symbols as in Figure 52).

the presence of other occurrences of lignite in the immediate neighbourhood is unlikely; similar small basins may occur in the surrounding area but they are probably concealed under several tens of metres of Pallinup Siltstone and could only be found by drilling.

PROPERTIES OF LIGNITE

In this report the term lignite is used for a consolidated member of the coal series with more than 30 per cent moisture and a moist calorific value of less than 19.3 MJ/kg (Lord, 1952). The following properties will be discussed:

(1) Specific gravity
(2) Proximate analysis
(3) Calorific value
(4) Crude oil content
(5) Montan wax content and quality.

All analyses of samples collected during this investigation have been made by the Government Chemical Laboratories and are given in full in Appendix 1.

1. Specific Gravity. Specific gravity was determined by displacement of water and was measured on the samples as received. Values ranged from 1.17 to 1.49 with the average being 1.3.

2. Proximate analysis. Proximate analyses of Fitzgerald River lignite have been published previously by Wilson (in Maitland, 1922) and Blatchford (1929). These analyses, together with ones obtained during this study are summarized in Table 24, where they can be compared with proximate analyses of lignites from California and Victoria. The Fitzgerald River lignite is characteristically high in moisture and ash.

TABLE 24A. PROXIMATE ANALYSES, GROSS CALORIFIC VALUE AND CRUDE OIL CONTENT OF VARIOUS LIGNITES

Lignite Sample	Proximate Analyses				Gross Calorific Value* (MJ/kg)
	Moisture	Volatile Matter	Fixed Carbon	Ash	
Ione Formation, California (a)					
American Lignite Products mine	36·8	36·8	16·2	10·2	16·40
Edwin No. 2 mine	37·3	32·9	21·4	8·4	14·59
Victoria Brown Coal (b)					
Yallourn	66·3	17·7	15·3	0·7	8·71
Tanjil East	50·0	26·0	22·0	2·0	12·95
Fitzgerald River Lignite					
Drillhole I, top of bed	50·1	19·9	13·2	16·8	8·95
base of bed	52·4	19·1	13·4	15·1	9·25
Drillhole M, top of bed	56·8	21·6	15·1	6·5	10·59
base of bed	38·6	12·5	6·4	42·5	5·59
Wheeler's Shaft (c)					
top of bed 2·4–2·9 m	37·6	32·4	18·2	11·8	
1·8–2·4 m	42·5	27·7	17·3	12·6	
1·2–1·8 m	42·2	30·1	17·5	10·1	
61 cm–1·2 m	42·3	26·8	14·5	16·4	
base of bed 0–61 cm	33·1	24·8	14·2	27·9	
Drive near bottom of Wheeler's Shaft (c)					
top, over 84 cm	42·9	28·3	16·4	12·4	
base, over 84 cm	43·4	23·5	14·6	18·5	
Bore 1·6 km downstream from Wheeler's Shaft (c)	15·7	7·7	3·6	73·0	
Near junction of Fitzgerald and Susetta Rivers (d)	7·9	54·0	21·4	16·7	

* As received.
(a) Selvig and others, 1950
(b) Edwards, 1945
(c) Blatchford, 1929
(d) Maitland, 1922

TABLE 24B.

Lignite Sample	Crude Oil (bbls/tonne)
New South Wales oil shale (a)	
Capertee Valley, Permian coal measures	1·4–2·8
Marangaroo torbanite, Permian coal measures	6·8 (max.)
Queensland oil shale (a)	
Carnarvon Creek torbanite, Permian	0.9
Injune, Jurassic coal measures	0·7–1·3
Baffle Creek, Tertiary	up to 1·3
Fitzgerald River lignite (b)	
Wheeler's Shaft	0·3

(a) Turner, *in* MacLeod, 1966
(b) Blatchford, 1929

3. Calorific value. No figures for calorific value have been previously available for the Fitzgerald River lignite. The gross calorific value ranges from 5.59 to 10.59 MJ/kg; as may be seen from Table 24 these values are low when compared with Californian lignite, but about the same as the Victorian lignites.

4. Crude oil content. Blatchford (1929) gives figures for the crude oil extracted from lignite samples obtained from a drive near the bottom of Wheeler's Shaft. The average value is 0.3 barrels/t which is low compared to Australian oil shales (see Table 24).

5. Montan wax content and properties. The Government Chemical Laboratories supplied the following information on montan wax:

> "The term 'montan wax' applies in its restricted sense to the particular extraction of central German lignites. The term 'montana wax' is used in the broader sense to describe waxes extracted from lignites found in many parts of the world. These waxes, according to their origin, differ somewhat in the proportional make-up of the constituents but are quite similar in most respects to true montan wax.

"All crude montan or montana waxes contain three main constituents—resins, ester waxes and asphalt and they differ from each other in containing different amounts of each. Benzene extracts a crude wax containing resins, ester wax and some asphaltic material. Hexane extracts all the ester wax fraction with some resin but no asphalt. Benzene/alcohol azeotrope extracts resins, ester wax and much asphaltic material. The yield of crude wax extracted by benzene/alcohol azeotrope exceeds that of benzene which in turn is greater than the hexane yield. Xylol behaves similarly to benzene but gives slightly higher yields because of its higher boiling temperature.

"The resins form a group of substances of very complex and variable chemistry and the resin content of the various crude montan waxes depends on both the source of the lignite and the solvent used to extract the wax. The resin (inclusive of the asphalt) is generally the undesirable constituent of the crude wax and this usually means that to be widely suitable for commerce the wax must be purified to a more or less resin-free state containing less than about 10 per cent resin. However if the crude wax has suitable melting point and other physical characteristics such as hardness, surface gloss etc. it may well be a commercial proposition in the crude form regardless of high resin content.

"Montan waxes are composed of a mixture of chemical constituents and so do not have a sharp melting point but rather they melt over a range of several degrees of temperature to dark viscous liquids. The melting range of a benzene/alcohol extract is usually several degrees higher and broader than that of the corresponding benzene extract. In general it can be said that the higher and sharper the melting point of a crude wax, the better as far as commercial possibilities go.

"The saponification value is a direct evaluation of the total amount of esters plus free acids in a wax. It approaches a constant number for a particular kind of refined wax but if the wax contains much resinous material the significance of the saponification value becomes obscure as the presence of large amounts of resins will usually increase the saponification value.

"The acid value expresses the free fatty (or waxy) acid and is more of a variable than the saponification number.

"Chemical constants such as the saponification value and acid value are determined usually to identify and classify waxes and are not normally as important as the physical characteristics (melting point, colour etc.) with regard to commercial applications."

Forty samples from three drillholes (I, M and F) were analysed for montan wax (see Appendix 1). All samples were dried at 110°C before analysis. Each sample was extracted using benzene as a solvent; in addition hexane, benzene/alcohol azeotrope and xylol were used as solvents on every fifth sample. Benzene was chosen as the standard with which to extract all samples because (a) it extracts all the wax but not all the unwanted resin and asphaltic material and (b) comparable figures are available for benzene extracts from lignites in other parts of the world.

The benzene-extraction figures range between 0.72 per cent. and 8.47 per cent. with an average value of 2.3 per cent. Table 25 compares the amount of montan wax in the Fitzgerald River lignite with that extracted from other lignites. The most important conclusion to be drawn from such a comparison is the low yield of wax from the Fitzgerald River lignite.

TABLE 25. AMOUNT OF EXTRACTABLE WAXES IN VARIOUS LIGNITES

Sample	Percentage Wax Extracted		Comments
	Benzene	Benzene/ Alcohol Azeotrope	
Fitzgerald River lignite			
Drillhole I (A) Core 2	2·2	4·9	dried at 110°C
I (B) 2	2·2	2·7	,, ,,
I (B) 4	2·4	5·3	,, ,,
F 2	2·8	5·1	,, ,,
M 1	3·5	7·4	,, ,,
M 2	2·8	5·1	,, ,,
M (A) 1	3·8	7·4	,, ,,
M (A) 10	2·1	3·3	,, ,,
Ione Formation, California (a)			
American Lignite Products mine	14·2	....	air dried
Buena Vista mine	6·0	....	dried at 105°C
	7·1	10·6	air dried
Edwin No. 2 mine	6·0	....	dried at 105°C
	6·6	9·5	air dried
Victoria (b)			
Morwell	2·3		air dried
Germany (b)			
Oberroblingen	13–16		air dried
Nachterstedt	17–18		air dried
Range of values	1·5–18		air dried

(a) Selvig and others, 1950
(b) Vcel'ak, 1959

In order to determine certain properties of the extracted montan wax the samples were combined, as very little wax obtained from each individual sample. The samples were grouped into four bulk samples representing the upper and lower parts of the lignite bed in drillholes I and M and the results obtained are included in Appendix 1. Table 26 compares properties of Fitzgerald River montan wax with montan wax from America and Germany. The most instructive comparison is between the Fitzgerald River wax and that extracted from Ione Formation (California), which is used commercially. The Fitzgerald River wax has a lower melting range and a higher resin content than the Californian wax.

TABLE 26. SELECTED PROPERTIES OF MONTAN WAX EXTRACTED FROM VARIOUS LIGNITES

Sample	Melting Range (°C)	Acid Value	Saponification Value	Resin Content (per cent)		S.G.
				(I)	(II)	
Fitzgerald River Lignite						
Drillhole I upper part of bed	66–77	28	248	76·6	75·1	1·10
lower part of bed	66–76	27	242	78·3	....	1·09
Drillhole M upper part of bed	66–77	29	218	53·2	54·6	1·08
lower part of bed	68–79	31	189	73.2	73.5	1.10
				(III)	(IV)	
Ione Formation, California (a)						
American Lignite Products mine	80–83	51	114	34	....	....
Buena Vista mine	78–82	46	105	45	31	1·06
Commercial montan wax (a)						
Riebeck brand crude montan wax	81–85	27	95	23	....	1·03
American montan wax (b)	77–81	38	105	24	....	1·03

(a) Selvig and others, 1950
(b) Extracted from Ione Formation lignite

Determination of resin content
I Acetone solubility at 25°C
II Ethyl acetate solubility at 0°C
III Ethyl ether solubility
IV Ethyl acetate solubility at —10°C

ESTIMATE OF TONNAGE

An estimate of the tonnage of lignite and hence the amount of montan wax in the Fitzgerald River area can be made using the data obtained from drilling, geological fieldwork and chemical analyses. In making this estimate only the area of lignite in which drillholes I and M are situated will be considered (see Fig. 53); the area of lignite east of drillhole N is so small that neglecting it in the calculations will not seriously affect the final figure. Furthermore, the whole of the lignite area outlined in Figure 53 is included in the calculation; hence the estimate given here must be considered a maximum.

The estimate tonnage is obtained as follows:

Area underlain by lignite (see Fig. 53)	280,000 m^2
Assumed average thickness of lignite (from drillholes L and M)	3 m
hence volume of lignite	840,000 m^3
Specific gravity of lignite (as received ; average of 4 samples)	1·3
hence tonnage of lignite	1,092,000 t
Amount of montan wax (benzene extraction ; dry basis ; average of 40 samples)	2·3 per cent
Moisture content of lignite (average of 4 samples)	50 per cent
hence average amount of montan wax (wet basis)	1·2 per cent
Amount of montan wax in 1·1 million t of lignite	13,200 t

Hence about 15,000 t of montan wax is available for extraction from an inferred 1.1 million t of lignite with an average moisture content of about 50 per cent.

CONCLUSIONS

The main conclusions which can be made as a result of this investigation are as follows:

(1) Lignite is confined to the Werillup Formation which rests directly on Precambrian rocks. The formation crops out in the bed of the Fitzgerald River but elsewhere in the valley it is concealed by up to 12.5 m of Quaternary deposits

(2) One bed of lignite about 3 m thick is present in the area, and this only occurs near the junction of the Fitzgerald and Susetta Rivers and was penetrated in two of the 15 holes drilled (I and M)

(3) The total inferred reserves of lignite are estimated to amount to 1.1 million t.

(4) The ratio of the lignite to overburden is about 1:4

(5) The amount of montan wax extracted from the lignite by benzene ranges from 0.72 per cent to 8.47 per cent, and averages 2.3 per cent (dry basis)

(6) About 15,000 t of montan wax are available for extraction from the estimated tonnage of lignite

(7) The wax has a lower melting point and higher resin content than German and Californian waxes.

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APPENDIX 1

ANALYSES OF FITZGERALD RIVER LIGNITE SAMPLES

All analyses have been made by the Government Chemical Laboratories

1. Specific gravity, proximate analysis and gross calorific value

Sample Lab. No. (1972)	Drillhole I (A) Core 2 22050	Drillhole I (B) Core 5 22051	Drillhole M Core 1 22052	Drillhole M (A) Core 9 22053
Specific gravity (a)	1·31	1·25	1·17	1·49
Proximate analysis		per cent		
Moisture (b)	50·1	52·4	56·8	38·6
Ash	16·8	15·1	6·5	42·5
Volatile matter	19·9	19·1	21·6	12·5
Fixed carbon	13·2	13·4	15·1	6·4
	100·0	100·0	100·0	100·0
Gross calorific value		MJ/kg		
as received	8·95	9·25	10·59	5·59
Dry, ash free	27·10	28·50	28·76	29·45

(a) Specific gravity determined by displacement of water
(b) Determined by loss in weight on heating at 105°C

2. Montan wax content

Drillhole	Core	Lab. No. (1972)	Benzene	Hexane	Benzene-alcohol azeotrope	Xylol
			per cent : dry basis (a)			
I	1	22054	8·47			
I (A)	1	22055	2·44			
I (A)	2 top 70–52 cm	22056	2·22	0·99	4·89	4·23
I (A)	2 52–35 cm	22057	1.01			
I (A)	2 35–17 cm	22058	2·11			
I (A)	2 17– 0 cm	22059	1·06			
I (A)	3	22060	0·73			
I (A)	4 top 82–63 cm	22061	0·91			
I (A)	4 63–42 cm	22062	1·14			
I (B)	1	22063	0·94			
I (B)	2	22064	2·22	0·54	2·72	1·65
I (B)	3 top	22065	0·43			
I (B)	3 bottom	22066	0·72			
I (B)	4 top	22067	2·37	1·26	5·34	2·96
I (B)	4 bottom	22068	2·19			
I (B)	5 top	22069	1·75			
I (B)	5 middle	22070	1·96			
I (B)	5 bottom	22071	1·73			
I (B)	6 top	22072	1.72			
I (B)	6 bottom	22073	1·12			
F	2	22074	2·79	1·57	5·10	3·93
F	3	22075	4·58			
F	4	22076	5·77			
F (A)	auger sample	22077	0·99			
M	1 top 79–62 cm	22078	1·94			
M	1 62–43 cm	22079	3·50	1·32	7·43	5·34
M	1 43–26 cm	22080	2·59			
M	1 26–12 cm	22081	2·33			
M	1 12– 0 cm	22082	1·86			
M	2	22083	2·83	1·47	5·08	4·14
M (A)	1 top 68–48 cm	22084	4·14			
M (A)	1 48–30 cm	22085	6·55			
M (A)	1 30–13 cm	22086	2·00			
M (A)	1 13– 0 cm	22087	3·79	1·40	7·35	4·63
M (A)	2	22088	1·47			
M (A)	9 top 45–40 cm	22089	0·98			
M (A)	9 40–15 cm	22090	2·29			
M (A)	9 15– 0 cm	22091	2·13			
M (A)	10	22092	2·14	0·94	3·28	2·86
M (A)	11	22093	1·25			

(a) Samples dried at 110°C

3. Properties of montan wax.

Four bulk samples of montan wax were obtained by combining the benzene-soluble fractions in the following manner:

Bulk sample 1 Lab. Nos. 22054-22060 plus 22063-22066 (Drillhole I, upper part of lignite bed).

Bulk sample 2 Lab. Nos. 22061 and 22062 plus 22067-22073 (Drillhole I, lower part of lignite bed).

Bulk sample 3 Lab. Nos. 22078-22088 (Drillhole M, upper part of lignite bed).

Bulk sample 4 Lab. Nos. 22089-22093 (Drillhole M, lower part of lignite bed).

Bulk Sample	Drillhole I upper part 1	Drillhole I lower part 2	Drillhole M upper part 3	Drillhole M lower part 4
Melting range (°C) (a)....	66–77	66–76	66–77	68–79
Acid value	28	27	29	31
Saponification value	248	242	218	189
Resin content (per cent)				
(b)	76·6	78·3	53·2	73·2
(c)	75·1	....	54·6	73·5
Specific gravity (at 25°C)	1·10	1·09	1·08	1·10

(a) Determined by closed capillary method
(b) Acetone solubility at 25°C
(c) Ethyl acetate solubility at 0°C

APPENDIX 2

PALYNOLOGY OF SAMPLES FROM THE WERILLUP FORMATION, FITZGERALD RIVER AREA

by J. Backhouse

The following core samples from drillholes in the Fitzgerald River area were examined for palynomorphs:

Drillhole	Core	Depth in metres	Lithology	F. No.
F (A)	Auger	15·12	Lignite	
I (B)	5	5·12– 5·89	Lignite	
M	2	15·90–16·62	Lignite	
F (A)	2	3·65– 4·00	Black carbonaceous shale	8321
G	2	6·71– 7·47	Dark grey siltstone	8322
K	1	13·73–14·49	Light grey siltstone with carbonaceous inclusions	8323

The three lignite samples were prepared using fuming nitric acid. A considerable quantity of plant tissue was recovered from them, but no spores or pollen grains were observed.

The remaining samples were processed by routine palynological methods. The shale sample from drillhole F (A) (F 8321) contained abundant plant tissue but only a few spores and pollen grains. However the other two samples from drillholes G and K contained good assemblages of spores and pollen.

F 8322, Drillhole G, 6.71-7.47 m

Spores and pollen:

Gleicheniidites sp.
Dictyophyllidites cf. *D. concavus* Harris
Nothofagidites cf. *N. emarcida* (Cookson)
Proteacidites sp.
Ericipites scabratus Harris
Dacrydium florinii Cookson and Pike

Age: Early Tertiary
Environment of deposition: Probably non-marine.

F 8323, Drillhole K, 13.73-14.49 m

Pollen:

Proteacidites annularis Cookson
P. pachypolus Cookson and Pike
Proteacidites cf. *P.* sp. 1 Hekel 1972
Triorites harrisii Couper
Casuarinidites cainozoicus Cookson and Pike
Nothofagidites cf. *N. hetera* (Cookson)
N. cf. *N. emarcida* (Cookson)
Santalumidites cainozoicus Cookson and Pike
Malvacipollis diversus Harris
Tricolpites sp.
Ericipites scabratus Harris
Dacrydium florinii Cookson and Pike

Age: Early Tertiary (Late Paleocene to Eocene)
Environment of deposition: Probably non-marine

Comments:

The abundance of pollen grains seems to be inversely proportional to the amount of carbonaceous material in the samples. The reason for this is not clear. No well documented Tertiary floras from Western Australia are available for comparison and the age determinations are based mainly on floras described from the Eastern States.

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16331/7/73

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